UNIVERSITY OF TASMANIA

Thesis:

Strategies for Sustainable Morphological Remediation of the Tamar River Estuary and other Similarly Degraded Estuaries

by

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Abstract

When anthropogenically induced morphological change within estuaries becomes irreversible, hysteresis is established and mitigating projects are required to undo any degradation. The morphologically degraded Tamar River estuary in Tasmania Australia typifies the universality of problems and solutions pertaining to estuaries in Australia, North America, Europe and the UK. Historically, restoration projects proposed for the Tamar were analogues of projects elsewhere, for which full repercussions are emerging. Barrages and weirs for example, unintentionally altered the hydrodynamics with negative long-term morphological consequences. Within the Tamar, recently mooted projects supposedly reduced the flood dominance of tides. Since the 1880s, silt management was by dredging (now cost prohibitive); replaced in recent years by silt raking. Neither process addresses the root-cause of the degradation.

The aim of this thesis was to develop and model sustainable solutions (proven and novel) for hysteretic degraded estuaries such as the Tamar, whilst identifying projects having potentially unacceptable trade-offs. The multifaceted methodology reviewed datasets pertaining to tidal heights, bathymetry and land elevations for the Tamar; examined asymmetrical tides, net sediment flux and establishment of equilibrium; developed a First Order Morphological Response Model (FORM) to review and evaluate proposed projects; used FORM on four international examples, and evaluated the effectiveness of barrages as mitigators of sea-level rise.

Tidal asymmetry results showed that flood velocity bias persisted and maximised at equilibrium, the inference being their removal is counterproductive. A feedback loop developed at equilibrium (driven by M4 and M6 harmonics); deposition on the banks led to slumping into the constantly scoured channel resulting in a net zero sediment flux. FORM modelled the new equilibrium of five putative barrages within the Tamar. Equilibrium established from a persistent flood velocity bias, ultimately resulting in a net loss of physical amenity below the barrage and unsatisfactory ecological trade-offs both upstream and downstream. Another study of four international barraged systems showed morphological degradation with some mitigation of sea-level rise in each head-pond but potential to increase tidal ranges downstream, thereby exacerbating sea-level rise. Neither study justified the installation of a barrage in the Tamar. Projects designed to remove or mitigate reduced estuarine and freshwater flow would be beneficial in restoring some amenity to the Tamar with potentially up to 8 million m^3 of silt permanently removed. Those projects synergistic with nature proved prospective, whereas those antagonistic to nature would fail. Results inform a more sustainable management of estuaries in general with emphasis on a proactive, rather than a reactive paradigm.

Declaration of originality

I hereby declare that this thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material which infringes copyright.

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Authority of access

Ian M Kidd 30th October 2016

Candidate's signature Name Date

Dr Andrew Fischer 30th October 2016

Supervisor's Signature Name Date

Statement regarding published work contained within the thesis

The body of this thesis includes three original papers published in peer reviewed journals and two original papers in review, in peer reviewed journals. The paper entitled "Tidal heights in hyper-synchronous estuaries" was not peer reviewed and is included in Appendix B rather than the body of this thesis. An additional peer reviewed paper co-authored by me (not written as part of this thesis) is in Appendix A, and a magazine article co-authored by me (written during this study but not as part of this thesis) is in Appendix C. The core theme of the thesis is the development and evaluation of various remediation strategies to combat the excessive silt accumulation which has occurred in the upper Tamar River estuary in Tasmania Australia. The ideas, development and writing of all the papers in the thesis were the principal responsibility of myself, the candidate, working within the Institute for Marine and Antarctic Studies at the of University of Tasmania, under the supervision of Dr Andrew Fischer of the University of Tasmania, and Assoc. Professor Shuhong Chai of the University of Tasmania. Professor Jenny Davis of Charles Darwin University has contributed significantly to this project and has co-authored four of the papers and Mr Michael Seward contributed one co-authorship. The inclusion of co-authors reflects the collaborative nature of the research conducted during the course of this PhD program.

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Statement of co-authorship

The following chapters comprise papers peer reviewed or in review. My contribution to each data chapter involved the following:

Thesis chapter	Publication title	Publication status	Nature and extent of candidate's contribution
2	Equilibrium imbalance due to sediment raking influences M2 tidal constituent, M4 and M6 harmonics and tidal asymmetry	In second review	Conception, design, data collection, data analysis, manuscript preparation
3	A First-Order Morphological Response Model (FORM) for predicting hydrologically induced bathymetric change in Coastal-plain Estuaries	Published	Conception, design, data collection, data analysis, manuscript preparation
4	A scenario-based approach to evaluating potential environmental outcomes following a tidal barrage installation	Published	Conception, design, data collection, data analysis, manuscript preparation
5	Total exclusion barrages as sea-level rise mitigators: The morphological trade-offs for new installations	Published	Conception, design, data collection, data analysis, manuscript preparation
6	Bathymetric rejuvenation strategies for a morphologically degraded estuary	In Print	Conception, design, data collection, data analysis, manuscript preparation

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

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3	Associate Professor Shuhong Chai	National Centre for Marine Engineering and Hydrodynamics, University of Tasmania. Supervisor
4	Professor Jenny Davis	University of Canberra; Charles Darwin University
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6	Prue Hamill	University of Tasmania

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Paper 1, Equilibrium imbalance due to sediment raking influences M2 tidal constituent, M4 and M6 harmonics, tidal asymmetry and net sediment flux: Located in Chapter 2					
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Located in Chapter 4

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Paper 4, Total exclusion barrages as sea-level rise mitigators: The morphological trade-offs of new installation Located in Chapter 5					
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Paper 5, Bathymetric rejuvenation strategies for a degraded estuary:

Located in Chapter 6

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<tr><td>Contributor</td><td>Conception
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Paper 6, Tidal heights in hyper-synchronous estuaries: Located in Appendix B					
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200 Years of mud and misunderstanding Located in Appendix C					
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GIS project: Potential tidal and flood inundation impacts on Launceston and suburbs Located in Appendix F					
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I have so many other people to thank and I do so in chronological order. This journey began with Jenny and I strolling along the Tamar waterfront aghast at the scene of degradation, when she announces that no such problem has been solved anywhere without looking into the flow. I admit to being somewhat bemused and retorted that the Tamar had been in the too hard basket for 200 years and that a bit of extra flow was unlikely to help. She remained unperturbed and contacted a local councillor (the late) Jeremy Ball with ideas for adaptive management of the problem. One thing led to another and eventually the Upper Tamar Rejuvenation Committee (UTRP) was established under the watchful eye of Jeremy and other community members including, Jim Guy, Peter Newman, Amanda Locatelli, Andrew Fullard, Andy Fischer, Neil Bose, Shuhong Chai, Alan Birchmore, Robert Dobrzynski, Andrew Baldwin, Mike Seward, Jenny Davis and me. Many thanks to all members; you were instrumental in me beginning this journey. I knew I was on to something when I presented my extremely sceptical father (Kay) with an early version of Davis and Kidd 2012 and he was instantly ‘converted’ from ‘dredging is the answer’, so thanks dad!

Thanks to Professor Neil Bose for your encouragement to enrol and to all those at AMC who made that possible. Thanks also to Associate Professor Gregor MacFarlane and Professor Paul Boon for providing references. Thanks also to Andrew Boulton for the one-on-one paper writing course and all my fellow authors; Andy Fischer, Shuhong Chai, Jenny Davis, Mike Seward and Prue Hamill.

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Thank you all for helping make this journey such a rewarding experience.

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LIST OF SYMBOLS AND ABBREVIATIONS

2D	two dimensional
3D	three dimensional
ADP	Acoustic Doppler Profiler
AGI	angle of greatest influence
AHD	Australian Height Datum
AMC	Australian Maritime College
AOD	above ordnance datum
BCR	benefit cost ratio
C	sediment carrying capacity
CAMBA	China Australia migratory bird agreement
DEM	digital elevation model
f	friction factor
FORM	First Order Morphological Response Model
GPS	Geographic Positioning System
h	mean hydraulic depth
H_b	Height of bank above MLWL
HR	Home Reach
HW	high water
HWL	High water level
IPCC	Intergovernmental panel on climate change
JAMBA	Japanese Australia migratory bird agreement
K1	Diurnal tidal constituent
K2	First Harmonic of K1
L	estuarine length
LFA	Launceston Flood Authority
LW	low water
LWL	low water level
m	metre
M2	semidiurnal lunar tidal constituent
M4	Fourth harmonic of M1
M6	Sixth harmonic of M1
MHWL	mean high water level
MSL	mean sea level
MWL	mean water level
NEP	National estuary program
P, TP	Tidal prism
PCA	Principal component analysis
POST	Parliamentary office of science and technology
Q	river discharge
s	second
S	net sediment flux
SBE	slack before ebb
SBF	slack before flood
SLR	sea-level rise

SP	Seaport
SSE	sea surface elevation
SSL	spatial settling lag
T	tidal range
t	time
TEB	Total exclusion barrage
TEER	Tamar Estuary and Esk Rivers project
TSL	temporal settling lag
u	tidal velocity
V	total silt volume
v	shape number
v_c	channel storage volume
VLM	vertical land movement
v_s	intertidal storage volume
W	channel width
x	longitudinal distance from head of estuary
YB	Yacht Basin
yr	year
γ	$(1-\gamma)$ being proportional to the difference between the flood period and 12.4 hours
θ	tidal constituent phase angle
ς^*	tidal amplitude

CHAPTER ONE:

GENERAL INTRODUCTION

Chapter 1

General Introduction and Literature Review

1. Thesis title

Strategies for Sustainable Morphological Remediation of the Tamar River Estuary and other Similarly Degraded Estuaries

1.1 Research question

What factors influence the morphological degradation of estuaries and in particular, the upper Tamar River estuary; is the process reversible and to what extent? What sustainable solutions or strategies could be applied to this and other similarly degraded estuaries?

1.2 Background

This genesis of this thesis is the environmental degradation of the upper Tamar River estuary in northern Tasmania Australia. Problems in the Tamar are typical of many post-industrial estuaries worldwide; unintended morphological changes, loss of habit and breeding grounds for fish, birds and other fauna, pollution/water quality issues, exotic plant infestations, sewage disposal and dispersal (Duarte et al., 2014), and sea-level rise emanating from climate change and vertical land movement (Bingley et al., 2001). Degradation has generally resulted in the loss of amenity and other eco-system services offered by the estuary (Davis and Kidd, 2012). This study focusses on the morphological degradation in the upper Tamar River estuary and other selected estuaries in North America, Europe and UK. Successful and non-successful solutions from other estuaries are considered as analogues for the Tamar.

2. Literature review

2.1 Definition and classification of estuaries

In order to understand the processes operating in an estuary it is necessary to provide a basic definition and to group similar estuaries into classes. Dyer (1997) extended previously developed definitions of an estuary (Cameron and Pritchard, 1963; Perillo, 1995) to,

"***an estuary is a semi-enclosed coastal body of water which has free connection to the open sea, extending into a river a far as the limit of tidal influence, and within which sea water is measurably diluted with fresh water derived from land drainage***".

The classification of estuaries is based on one or more physical characteristics; the ratio of freshwater input to evaporation (Pritchard, 1952a), classification by tidal range (Davies and Moses, 1964), synchronicity (Nichols and Biggs, 1985), topography (Pritchard, 1952b), morphology (Fairbridge, 1980) and salinity structure (Pritchard, 1955). Another classification is the quantified classification where different types are stages on a continuous sequence, usually involving dimensionless numbers or parameters and tidally averaged variables (Dyer, 1997). For the Tamar River estuary, the classification differs from the lower estuary to the upper estuary (Table 1.1). The change in classification of the Tamar from the upper to lower regions is unusual although not unique. For coastal-plain estuaries regime models are used to predict morphological change (see Chapter 4) and examples are presented in Chapters 3, 4, 5 and 6.

Table 1.1. Classification of the upper and lower Tamar River estuary, northern Tasmania Australia

Classification type	Lower estuary	Upper estuary
Input ratio	positive	positive
Tidal range	Meso-tidal	Meso-tidal
Synchronicity	Hyper-synchronous	Hyper-synchronous
Topography	Drowned river valley (ria)	Coastal-plain
Morphology	Transgressional	Progradational
Salinity	Stratified	Well mixed

2.2 Water circulation

Circulation, otherwise known as net current, non-tidal flow or tidal residual is the time averaged current due to gravitational effects (on water of different density or temperature), the river flow and wind (Valle-Levinson, 2010). Despite the diurnal or semi-diurnal tidal flow, the net flow is out of the estuary (Fig. 1.1). Density increases with increasing salinity and decreasing temperature and a gradient in water density is created when the lighter fresh water mixes with the heavier salt water. Gravitational circulation results as the fresh water gains salt, increases density, and sinks. Similarly, large differences in water temperatures can also drive gravitational circulation. Residual water circulation may be affected by large scale infrastructure (Meyers et al., 2014).

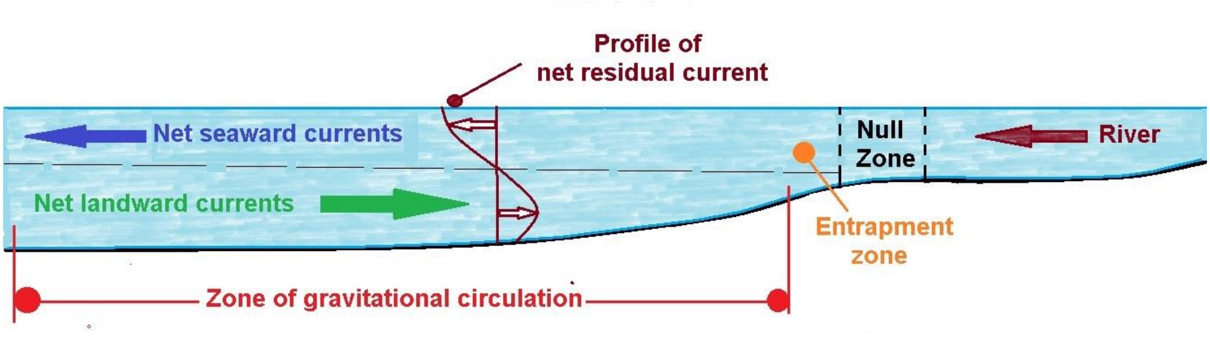


Fig. 1.1 Non-tidal water circulation within an estuary (Valle-Levinson, 2010)

2.2.1 Classification of estuaries by circulation mode

Most estuaries can be classified according to one of four circulation modes; classical, reverse, discharge or storage. Classical is shown at Fig. 1.1 where dense salt water is drawn into the estuary along the bed whilst the less dense fresher water leaves the estuary at the surface. In arid climates, evaporation rates may exceed fresh-water inflows resulting in higher salinities within the estuary than the open sea and the circulation is reversed. The high fresh-water discharge of estuaries such as the Mississippi and the net flow is ebb at all depths, is an example of discharge circulation. Storage circulation is very rare and the net circulation at all depths is into the estuary. Variations in fresh-water inflows, seasonal fluctuations, storm surges and wind conditions mean that circulation may vary temporally in some estuaries.

2.3 Tides, tidal constituents and harmonics

Tides affect the land surface (Cartwright and Melchior, 1999) the atmosphere (Covey et al., 2011; Dai and Wang, 1999) and the oceans (Doodson, 1921). Oceanic tides are either diurnal or semi-diurnal and consist of hundreds of constituents, which are sinusoidal waves produced by the gravitational influence of the moon and sun and the rotation of the earth (Stewart, 2008). Constituents with a period of less than half a day are harmonics of a primary constituent, whereas cycles of days, months and years are known as long term constituents. The orbit of the moon around the earth creates the greatest constituent (M2; M for moon and '2' for two tides per day) which has a period of 12.4206 hours. In estuaries the M2 constituent becomes distorted due to channel friction and convergence so that it is no longer sinusoidal and energy is transferred from M2 to harmonics of M2 such as M4, M6 and M8 (Speer and Aubrey, 1985). The combination of M2 and M4 is generally considered adequate to model the tidal influence on sediment dynamics in estuaries (Aubrey and Speer, 1985; Dronkers, 1986; Dyer, 1997; Friedrichs and Aubrey, 1988; Prandle, 2009; Speer and Aubrey, 1985). In the upper Tamar, M6 is unusually large and is greater than M4 and Chapter 2 discusses the ramifications for sediment flux and dynamic equilibrium in the upper estuary.

2.3.1 Tidal constituent analysis

Any signal can be decomposed into sinusoidal components using various forms of Fourier transform (Smith, 1997). The signal is transformed from the time domain to the frequency domain where the constituent frequencies appear as spikes in the zero-mean plot. For tidal signals, dedicated software (*t_tide or U-tide*) which simplifies the process are/is available as a plug-in(s) for Matlab (Pawlowicz et al., 2002) and analyses sea-height time series with a sampling period of one hour. The output is a list of the largest 60 or so constituents, their amplitudes with error, and phase angles with error.

2.4 Sediment dynamics

2.4.1 Turbidity maximum, flocculation

In longish estuaries such as the Tamar fine particles remain in suspension and do not precipitate easily. When in contact with saltwater the fine particles combine to form much larger particles (floccs) in a process known as flocculation (Eisma, 1986; Sholkovitz, 1978; Stone and Droppo, 1994). The formation of flocs and their settling velocity is a function of suspended sediment concentration and the degree of turbulence (Soulsby et al., 2013). The transportation dynamics of flocs differs from that of fine suspended sediment; in particular flocs deposit in water velocities < 0.1 $m.s^{-1}$ (Hjulstrom, 1939). The persistence of fine material in suspension creates a zone of high turbidity in the upper reaches of long estuaries (Chernetsky et al., 2010), known as the turbidity maximum. This is a natural phenomenon caused by the bathymetry of the estuary (Prandle, 2009) and does not necessarily indicate high sediment input levels from the catchment (de Jonge et al., 2014). The lower limit of the turbidity maximum coincides approximately with the head of the salt intrusion and varies with river discharge and semi-diurnal and neap-flood tidal cycles (Dyer, 1997).

2.4.2 Tidal asymmetry

A fundamental process at play in the Tamar River estuary (and most estuaries around the globe) is the asymmetry of the tides. Tidal asymmetry refers to the difference in velocity between flood and ebb tides and the corresponding difference in duration (Dyer, 1997).

Tidal asymmetry is caused by the interaction of the largest primary constituent with one or more of its harmonics. M2 is usually the largest primary constituent although in Venice Lagoon, Italy M2 is small and the interaction is (presumably) between K1 and the first harmonic K2 (Ferrarin et al., 2015). A similar K1:K2 interaction exists at the Murray Mouth in South Australia (Jewell et al., 2012). Depending on which harmonics are significant, asymmetry will exist as a velocity differential between the maximum flood and ebb flows, or possibly a time differential between the dwells at high and low tides (Dronkers, 1986). A full explanation is provided in Chapter 2. Gravitational circulation as mentioned above may also cause asymmetry particularly in stratified lower to mid regions of an estuary.

2.4.3 Sediment transport

Sediment transport in estuaries varies non-linearly with velocity as represented by the Hjulstrom curve (Hjulstrom, 1939) (Fig. 1.2). Clay for instance requires velocities over 1 $m.s^{-1}$ to erode, but once eroded remains in suspension and is transported at the same velocity as the neighbouring water molecules. At the other extreme gravel also requires velocities over 1 $m.s^{-1}$ to erode but deposits easily. Gravel is transported as bed load, rolling or bouncing along the bottom in a process known as saltation (Pethick, 1998).

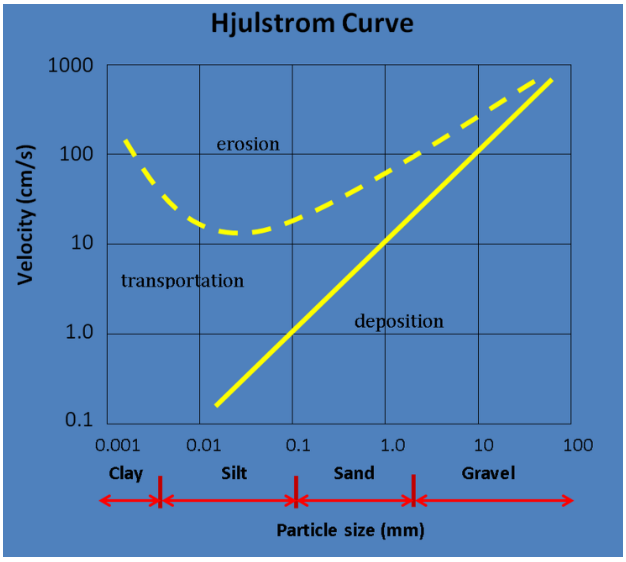


Fig. 1.2 Hjulstrom curve showing non-linear differential transport of solids within estuaries and rivers

Sediment transport and tidal velocity are inextricably linked. In the majority of instances, asymmetric tides produce higher peak velocities in the ebb or flood direction, leading to net sediment transport in the direction of greater velocity (ABPmer, 2008) (see Petitcodiac exception below). Ebb biased and flood biased channel types were identified by Dronkers (1986) which led to the defining of estuarine development stages (Pethick, 1994) (Fig. 1.3).

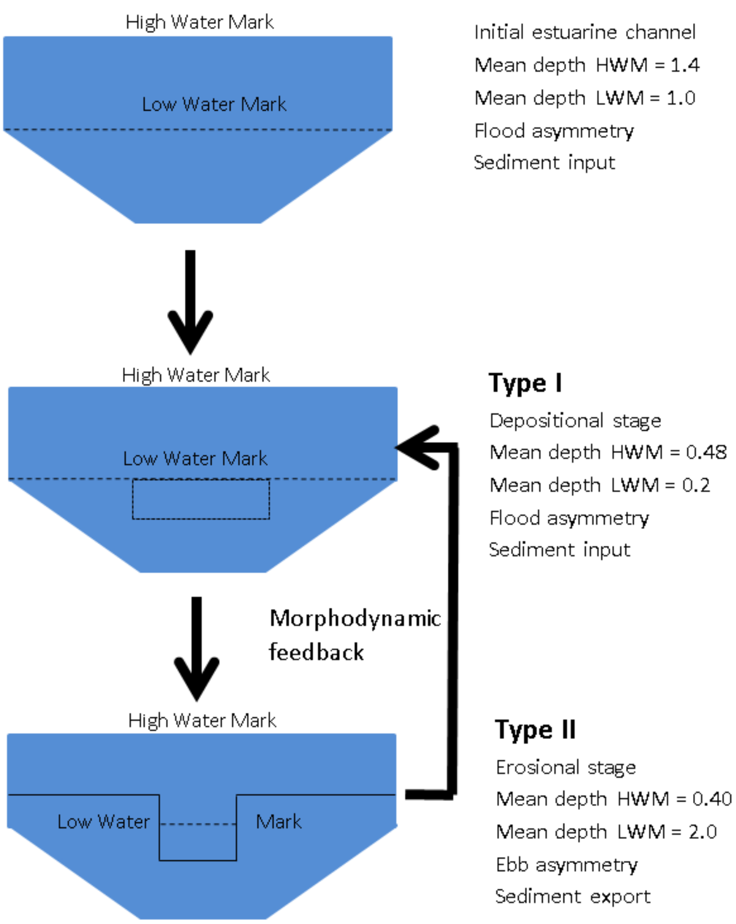


Fig. 1.3 Stages of estuary development and the morphodynamic feedback between type I and type II estuaries (Pethick, 1994)

Velocity-stage plots graphically illustrate tidal asymmetry by showing the magnitude of tidal velocities at different sea-surface elevations (SSE). A symmetric tide is circular or ovular whereas increasing distortion represents increasing asymmetry. Ebb or flood dominance is indicated by the area of the shape relative to the axes (ABPmer, 2008). Velocity stage plots for the Tamar are presented in Chapter 2.

2.4.4 Tidal asymmetry ratio

Dronkers (1986) derived an asymmetry ratio based on the form parameters of an estuary, assuming that morphological equilibrium equates to a uniform tide:

$$\gamma = \left(\frac{h+a}{h-a}\right)^2 \cdot \frac{S_{lw}}{S_{hw}} \tag{1}$$

where γ is defined from: $(1-\gamma)$ being proportional to the difference between the flood period and 12.4 hours (half the semi-diurnal cycle); *h* is the mean hydraulic depth given approximately by $h = a + V_{lw}/S_{lw}$, *a* is the tidal amplitude; S_{lw} is the surface area at low water; S_{hw} is the surface area at high water; and V_{hw} and V_{lw} are the volumes at high and low water respectively. Duijts (2002) refined this equation with terms for surface area of the channel at high ($S_{C.HW}$) and low water ($S_{C.LW}$), and found for strongly convergent channels

$$\gamma = \sqrt{\left(\frac{h+a}{h-a}\right)^2 \cdot \frac{S_{lw}}{S_{hw}} \cdot \frac{S_{C.HW}}{S_{C.LW}}} \tag{2}$$

Aubrey, Friedrichs and Speer produced a series of papers in the 1980s (Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988; Speer and Aubrey, 1985) in which the parameters *a/h* and v_s/v_c were identified as key indicators of asymmetry in a system (v_s is intertidal storage volume and v_c is channel storage volume). Their studies were based on observation, analytical theory and numerical modelling of US estuaries which are micro-tidal with a mean channel depth of 2.8 m (see Chapter 2 for further discussion).

2.4.5 Net sediment flux

Dronkers (1986) expanded the work of (Postma, 1954) relating to the effect of slack water around high and low tides, deducing that the differences in HW and LW slack through a cross-section produce a net sediment flux:

$$S = \mu^+\lambda^+ - \mu^-\lambda^- \tag{3}$$

where μ^+ (respectively, μ^-) is the amount of sediment settled on the bed during the period of HW slack (respectively LW slack) and λ^+ (respectively, λ^-) is the distance travelled by fluid parcels during the period of HW slack (respectively LW slack) during which the deposited material remains settled. Dronkers (1986) explained it thus:

"***The amount of sediment μ^+, which is settled per unit length at HW slack, will not follow the tidal motion before the ebb current reaches the critical speed for erosion. In this lapse of time the settled sediment is displaced with respect to the suspended sediment in a landward direction over a distance which on average equals λ^+. Around LW slack a similar displacement will occur of sediment mass, μ^- , in a seaward direction over an average distance, λ^- .***"

From equation 3 it is deduced that if slack duration at high water is greater than duration of low water slack then net sediment flux is flood biased and vice versa.

The movement of sediments by asymmetric tides is fundamental to bathymetric change, and the above analysis applies in most estuaries. However in estuaries which are significantly out of equilibrium, tidal velocities are higher in the case of *under* equilibrium and lower when *over* equilibrium. In extreme cases maximum velocity bias does not imply that net sediment flux will be in the same direction. This is evident in the Petitcodiac River estuary in New Brunswick Canada, where a net ebb sediment flux predominates following the opening of the Moncton Barrage in 2010 (see Chapters 3 and 5), despite the velocity being flood biased. Tides are semi-diurnal with two tidal bores arriving at Moncton per day, the tidal velocity remains highly flood dominant (Fig. 1.4), with flood duration <3.5 hrs and ebb duration ~ 9 hrs.

When the barrage was opened in 2010, the tidal prism below the barrage increased due to the additional tidal volume of the headpond, which increased the flood and ebb velocities below the barrage. The ebb velocity increased sufficiently to maintain coarse sediment in suspension which would normally have settled out, and given the longer duration of the ebb tide, net sediment flux is ebb biased. In this instance, net sediment flux is determined by the asymmetry of the tidal flow duration rather than asymmetry of the peak velocities. As a result, the system is slowly returning to the pre-barrage state (Van Proosdij et al., 2009), although complete restoration in unclear. The morphological change due to the installation of the barrage in 1968 to the re-opening in 2010 is presented below in section 2.6.

(a)

(b)

Fig. 1.4 The Petitcodiac River estuary 13th September 2015 (a) a small tidal bore and the start of the flood tide at 10:30 am (focal length 55 mm) and (b) The ebb tide had commenced by 13:21 hrs (focal length 26 mm). See also Chapters 3 and 7. Photos I Kidd

2.4.6 Sediment supply

The morphological change evident in the Petitcodiac River from 1968 to 2010 requires a source of sediment. Sources of sediment entering estuaries are either marine or terrestrial (Pethick, 1998). Longshore drift moves coastal sediments along the coastline which enter estuaries on flood tides and storm surges. Land-based sediments are carried into estuaries via rivers, streams and storm water drains and originates from within the watershed or catchment of the estuary. Over 90% of all marine sediments are of riverine origin, less than 5% of beach sediments originate from eroded coastline with the remainder being of glacial and biogenic origin (Valentin, 1954).

2.4.7 Sediment management

In many estuaries sediment management is required to maintain or create the desired amenity or ecosystem services. Techniques include structures to control water flow (breakwaters, jetties, levees, causeways, barrages, hard-walls) (Prumm and Iglesias, 2016), vegetation, erosion control, dredging silt raking and catchment management.

Dredging

Dredging is the physical removal of bottom sediments and disposing of them elsewhere, either within the same waterbody or on land. Dredging is conducted for many reasons; capital dredging to create new channels, berths or harbours; maintenance dredging to deepen waterways or channels; and preparatory dredging associated with construction of bridges and piers. In estuaries dredging causes in an imbalance in the equilibrium status of the estuary and one-off capital dredging usually requires ongoing maintenance dredging as the system attempts to regain equilibrium by accretion of more sediment (Healy et al., 1997). Dredging can be an expensive undertaking to the point of being cost prohibitive and depending on the jurisdiction may require legislative approval and environmental permits. This is the case in the Tamar River Tasmania where dredging, drying and disposal of sediment amounts to ~ AU$42 per tonne and environmental permits are prohibitively arduous (www.examiner.com.au?story/441627/dreging-tamar-plan-stuck-in-mud/ accessed 2nd July 2016).

Silt raking

The process of silt raking is not well documented in the literature. During this study an annual silt raking program was undertaken in the upper reaches of the Tamar River estuary to move silt downstream on ebb tides and high flow events. In 2013 the program moved up to 200,000 m^3 of silt downstream and placed the upper estuary out of the equilibrium state. In 2014 and 2015 the raking was less successful due mainly to the lack of flood events. Following each raking season, the displaced silt partly returned over the subsequent months which provided the opportunity to monitor the interplay between the tidal asymmetry and the equilibrium imbalance of the system. Chapter 2 analyses sea-surface elevation data collected over 22 months and tidal velocity data collected over 4 months. The study provided a greater understanding of the interplay of tides, turbidity, net sediment flux and equilibrium (or more precisely dynamic equilibrium).

Catchment management

Erosion control within a watershed or catchment is always desirable as a measure of inhibiting high sediment input to rivers and estuaries (Davis and Kidd, 2012; Foster et al., 1986) and to maintain productivity and ecological health of the catchment. Sediment entering the system from the catchment may become trapped especially in long estuaries such as the Tamar River and is only removed in the event of flooding. However high turbidity is not necessarily correlated with high sediment input but rather a natural function of bathymetry (Prandle, 2009) or as a consequence of forced change of bathymetry (de Jonge et al., 2014). Foster et al. (1986) found that the North and South Esk rivers which feed into the Tamar

River are ***"very clean even during floods and that no substantial reduction in the silt load can be achieved from general catchment erosion control measures"***.

2.5 **Morphological change in estuaries**

The importance of estuaries to the well-being of mankind cannot be understated. Many of the world's cities are based around estuaries which (initially) provided food, fresh-water and harbours for trade and commerce (Prandle, 2009). The estuary influenced patterns of urbanisation which in turn had sociological ramifications for the human population. Anthropogenic influences on estuaries are ecological and morphological and together with pollution, combine to degrade the estuary from its natural state (Borja et al., 2010). A negative feedback loop is thus established until degradation becomes unacceptable and remediation is required. Restoration to the natural state is rarely an option as a degree of hysteresis is usually present (Davis and Kidd, 2012; Suding and Hobbs, 2009).

Morphological change in estuaries is an ever present phenomenon and is due to natural and anthropogenic forcing. Anthropogenic morphological change in the Humber Estuary in the UK dated from Roman times (Morris and Mitchell, 2013; Townend et al., 2007) and other ancient civilisations were adept at manipulating water courses for agriculture, water supply and lifestyle (Gibson et al., 2010). Tidal flats and vegetated marshes represent attractive, easy pickings for agriculture, and a process known as canalisation, draining by use of tidal levees (or dykes) and simple valve systems, was and remains a common practice within the developed and developing world. Many estuaries in the UK Europe and the US are effectively now tidal canals (Morris and Mitchell, 2013) as is the upper Tamar River estuary, where tidal and flood levees now prevent the tidal inundation of approximately 4 km^2 of old tidal flat with an estimated tidal prism loss since 1806 of 1,000,000 m^3 (Davis and Kidd, 2012). In Chapter 3 it is shown how this tidal prism loss has caused >13,000,000 m^3 of silt to accrete over the silt belt of the upper estuary.

2.5.1 Bathymetric migration

Davis and Kidd (2012) raised the concept of bathymetric migration as it relates to aggradation at the tidal extremity of the Tamar River estuary. Chapter 5 explores this concept more thoroughly with four international examples and demonstrates the usefulness of the concept in assessing the trade-offs in terms of ecosystem services with mitigation of potential sea-level rise at the four sites, each having been altered by installation of a barrage. This chapter was the basis for a presentation by the author at the ECSA55 conference held in London in September 2015 (http://www.ecsa-news.org/ accessed 27th June 2015) (see Chapter 5). The concept of bathymetric migration was emphasised as it represents a fundamental principle of the regime model presented in Chapter 3.

2.5.2 Morphological change due to sea-level rise

Sea-level rise (SLR) plays an important part in morphological change in estuaries. Sea-levels rose approximately 60 metres in the last post-glacial period (Holocene) from 20,000 to 8,000 years ago, flooding coastal areas and rivers, and forming many of the present day estuaries. Over the last 8,000 years global sea-levels remained relatively stable but rose ~195 mm between 1870 and 2004. Satellite data show an increase of 3.3 ± 0.4 mm per year from 1993 to 2009 (Nicholls and Cazenave, 2010). The rate has increased again since 2009 (www.cmar.csiro.au/sealevel/ accessed 24th June 2016) now approaching 5 mm per year (Fig 1.5).

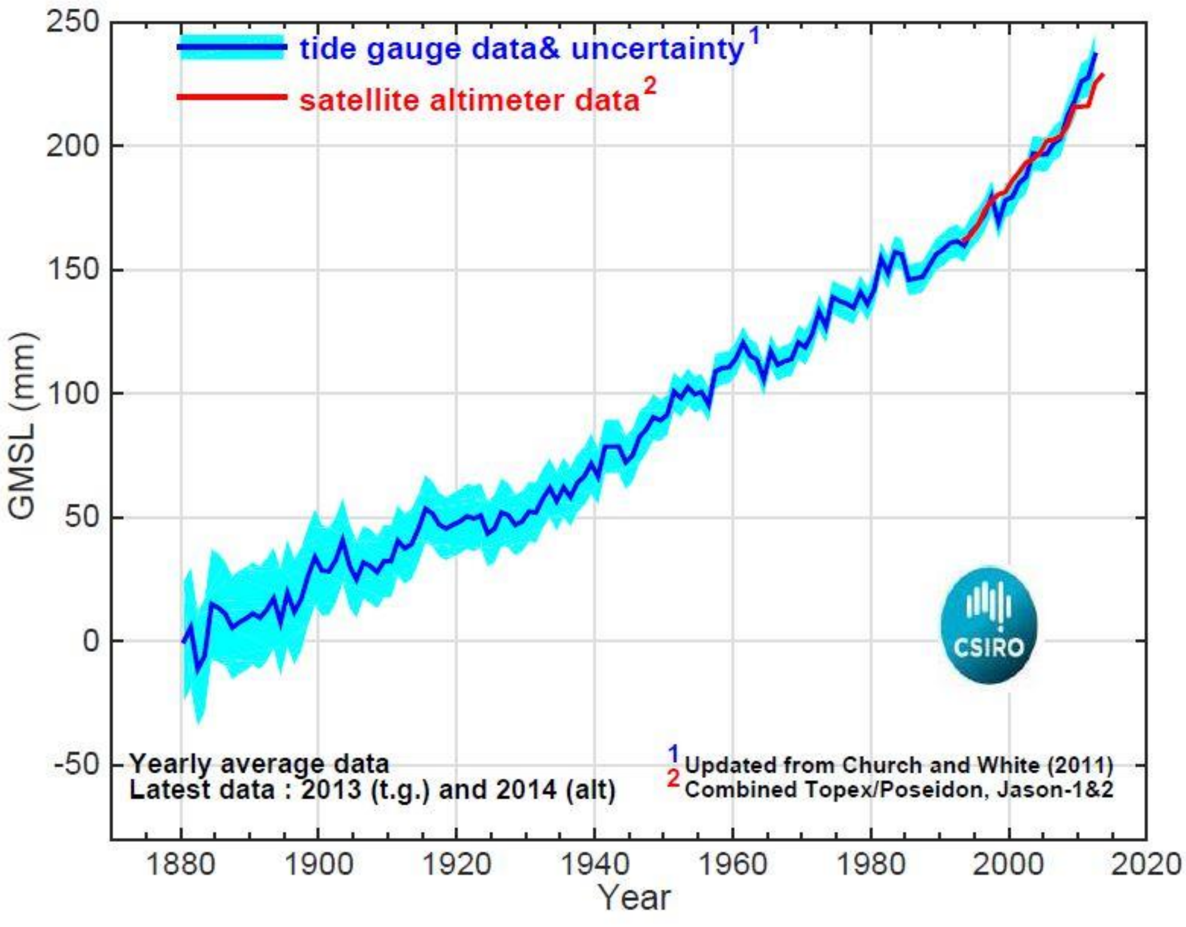
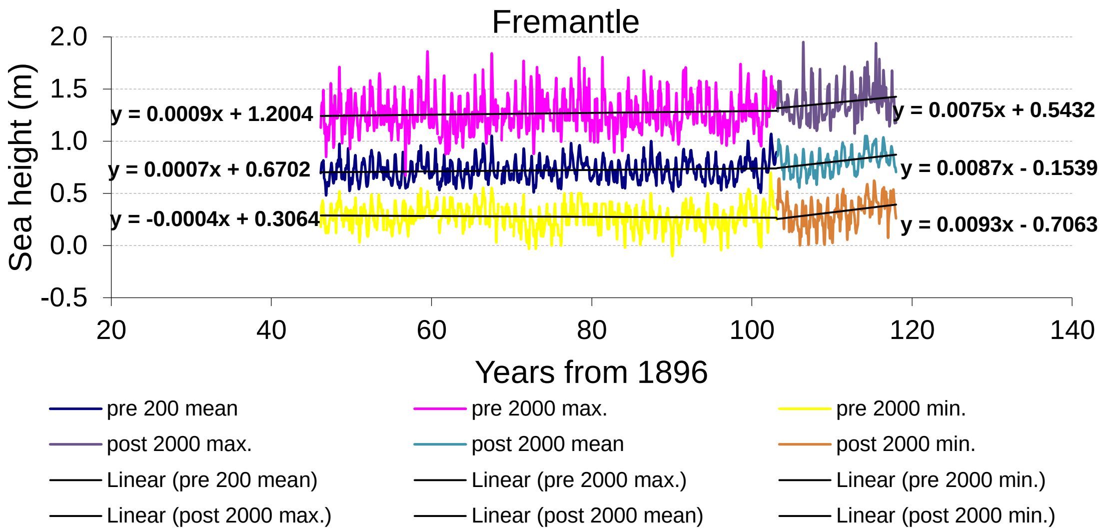


Fig. 1.5 Global sea-level-rise as measured by tide gauges and satellite; source www.cmar.csiro.au/sealevel/ (accessed 24th June 2016)

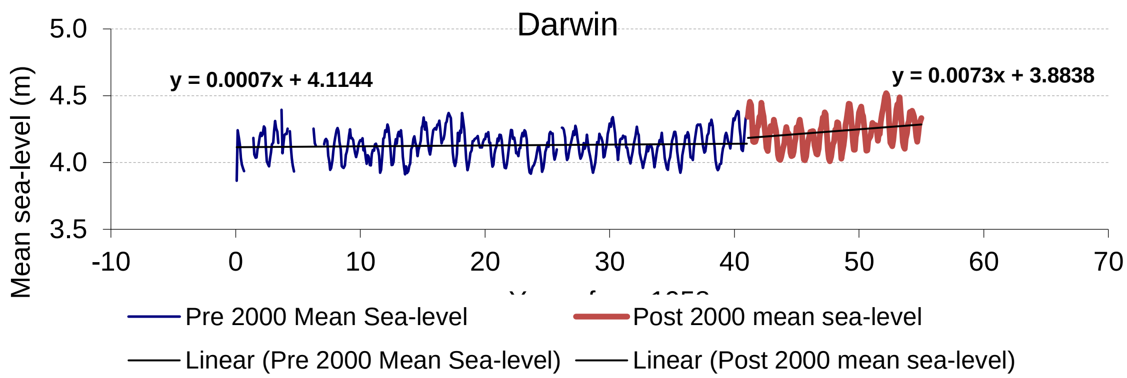
The present rate of increase equates to the previous rise of 60 metres over 12,000 years; i.e. 5 mm per year but an increase is forecast (Church and White, 2006, 2011), indicating a transgression from a period of relative sea-level stability to one of dramatic increase. In Australia, sea-level-rise is distorted by the El Niño Southern Oscillation (ENSO) (White et al., 2014), which complicates the calculation of SLR. Vertical movements in landmass also produce local anomalies (Bingley et al., 2001) with Australian observations showing considerable variation between stations (Fig. 1.6). The vertical landmass movement (VLM) is caused by iso-static adjustment (Bingley et al., 2001) or tectonic movement of the earth's plates and satellite data are now used in preference to tidal gauge data to remove the influence of VLM. Ocean basins may also deform (static effect) due to land-based water redistributions causing a 30% increase in the tropics and negative influences close to the melting bodies (Cazenave and Cozannet, 2014). Steric effects arising from changes in wind stress, heat and freshwater fluxes also produces regional variations in SLR (Cazenave and Cozannet, 2014).

Data for Low Head at the head of the Tamar River contain an error in the datum used (Kidd et al., 2014) (included at Appendix B) which had not been corrected as of 27th June 2016, but the trend should match that of Devonport, 37 km to the west. The trends evident in Fig. 1.5 and Fig. 1.6 must be viewed with due caution given the relatively brief time frame of the recent acceleration.

(a)


Fremantle
Sea height (m)
2.0
1.5
1.0
0.5
0.0
-0.5
y = 0.0009x + 1.2004
y = 0.0007x + 0.6702
y = -0.0004x + 0.3064
y = 0.0075x + 0.5432
y = 0.0087x - 0.1539
y = 0.0093x - 0.7063
20
40
60
80
100
120
140
Years from 1896
pre 200 mean
pre 2000 max.
pre 2000 min.
post 2000 max.
post 2000 mean
post 2000 min.
Linear (pre 200 mean)
Linear (pre 2000 max.)
Linear (pre 2000 min.)
Linear (post 2000 max.)
Linear (post 2000 mean)
Linear (post 2000 min.)

(b)


Darwin
Mean sea-level (m)
5.0
4.5
4.0
3.5
y = 0.0007x + 4.1144
y = 0.0073x + 3.8838
-10
0
10
20
30
40
50
60
70
Pre 2000 Mean Sea-level
Post 2000 mean sea-level
Linear (Pre 2000 Mean Sea-level)
Linear (Post 2000 mean sea-level)

(c)

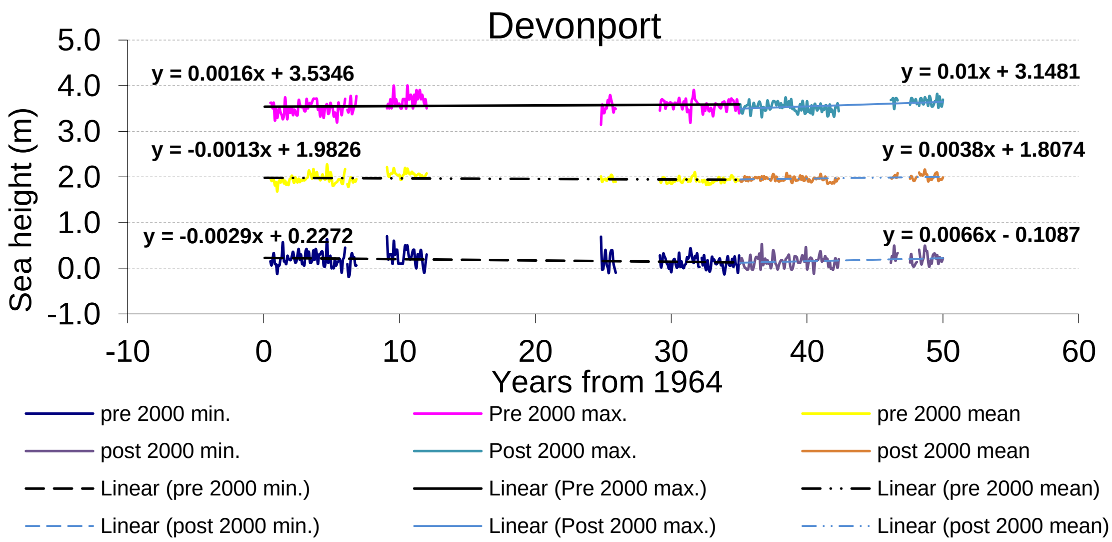

Devonport
Sea height (m)
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
y = 0.0016x + 3.5346
y = 0.01x + 3.1481
y = -0.0013x + 1.9826
y = 0.0038x + 1.8074
y = -0.0029x + 0.2272
y = 0.0066x - 0.1087
-10
0
10
20
30
40
50
60
Years from 1964
pre 2000 min.
Pre 2000 max.
pre 2000 mean
post 2000 min.
Post 2000 max.
post 2000 mean
Linear (pre 2000 min.)
Linear (Pre 2000 max.)
Linear (pre 2000 mean)
Linear (post 2000 min.)
Linear (Post 2000 max.)
Linear (post 2000 mean)

Fig. 1.6 Sea-level time series (a) for the port of Fremantle Western Australia; mean sea-level rose < 1 mm/yr up to 2000 and by 8.7 mm.yr^{-1} from 2000 to 2014; (b) sea-level trends for the port of Darwin Northern Territory. Mean sea-level rose < 1 mm.yr^{-1} up to 2000 and by 7.3 mm.yr^{-1} from 2000 to 2013 and (c) sea-level trends for the port of Devonport Tasmania. Mean sea-level fell > 1 mm.yr^{-1} up to 2000 and rose by 3.8 mm.yr^{-1} from 2000 to 2014. Data source www.bom.gov.au accessed September 2016

2.5.3 Mitigation of sea-level rise

In recent years the mitigation of SLR has been given greater attention from local to national scales (Stive et al., 2013), as has the ability of estuaries to cope with SLR (Van Goor et al., 2003). Prandle and Lane (2015) assessed the vulnerability of 96 UK estuaries against four indices which they developed. Papers from the ECSA55 conference were not available at time of writing but one of the conference's themes was 'Estuaries and coasts in the future: Prediction and adaptation'. A consistent message was avoiding knee-jerk reactions, the need to provide sufficient accommodation space, removal of barriers to sediment movement and appropriate urban planning and regulations (pers. obs.). In Chapter 5 the use of total exclusion barrages for mitigation of SLR is discussed.

2.5.4 Inter-tidal flats and saltmarsh

Tidal flats are capable of keeping pace with sea-level rise provided the sediment supply is sufficient (Williams et al., 2002) although if the predicted rates > 5 mm.yr^{-1} of sea-level rise eventuate then drowning is the most likely outcome (Van Goor et al., 2003). Wind waves influence tidal flat morphology (Fagherazzi et al., 2007; Talke and Stacey, 2008) and play an important role in sediment movement (Dronkers, 1986; Friedrichs and Aubrey, 1988).

2.6 Morphological Modelling

Prediction of morphological change in estuaries has been described as an ambitious objective (Uncles, 2002). Models are of three types; Top-down, Hybrid and Bottom-up (Emphasys Consortium, 2000). Top-down models use observational data and empirical relationships in forming an understanding of functioning and behaviour to make predictions over long time scales (years). Bottom-up models work from small scale physical processes as building blocks for prediction of changes over larger scales and time frames of weeks. Hybrid models integrate the two so that intermediate time scales of weeks to years are covered. The FORM model developed in Chapter 3 is an example of a Top-down model. FORM is based on regime theory which Emphasys Consortium (2000) define as;

"…predicts long term morphological change through the empirical regime theory relationship between estuary cross-section and tidal prism. This approach investigates morphological change (estuary width, depth, length and plan-form) based on a change in the tidal prism".

Regime theory represents an Occam's razor (Young et al., 1996) approach to morphological modelling but is surprisingly accurate (Emphasys Consortium, 2000). All models require inputs or a set of known boundary conditions. FORM for instance requires plan-form data, width against length, tidal range against length, storage volumes and river width, to calculate tidal prism at any distance from the head. FORM introduces the concept of bathymetric migration which applies when the tidal prism is permanently altered. The Petitcodiac River in New Brunswick is presented as an example (Fig. 1.7).

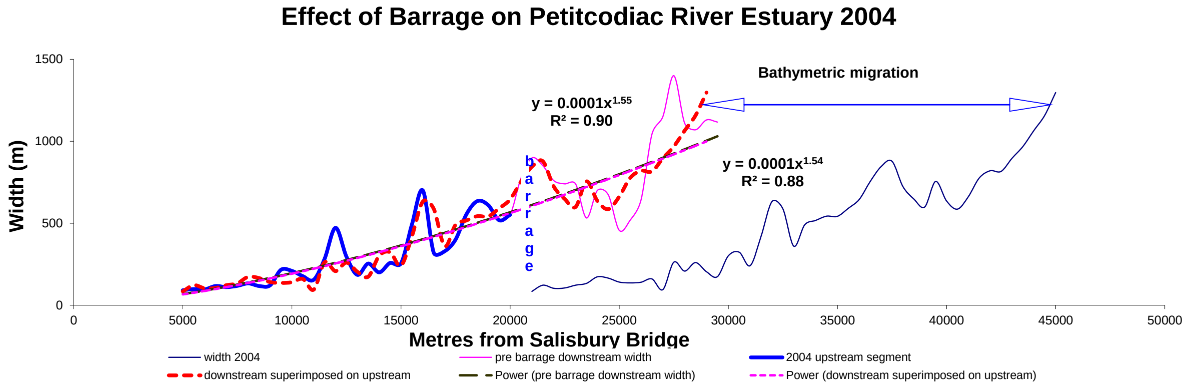


Fig. 1.7 Bathymetric migration in the Petitcodiac River following the installation of the Moncton Barrage in 1968. The bathymetry migrated from the head of the old estuary to the barrage, but since the opening of the barrage in 2010 the remnant estuary is slowly returning to the pre-barrage state; from (Kidd et al., 2016a)

Bottom-up models require a mathematical understanding of processes such as hydrodynamics, sediment transport and how they influence salt transport/mixing, salinity and stratification. The mathematics is complex and simplifications are required to solve the equations resulting in errors compounded over the iterations of tidal cycles (Emphasys Consortium, 2000).

2.6.1 Hydrodynamic theory

Central to hydrodynamic theory are the Navier-Stokes equations which are based on the assumption that a fluid is a continuous substance rather than discrete particles and that the fields of interest (pressure, flow, velocity, density and temperature) are differentiable. The equations derive from the continuity of mass, momentum and energy and are applied over a finite arbitrary volume (Galdi, 2011).

This thesis does not delve into hydrodynamic theory or Bottom-up modelling. A black box 2D model of the Tamar River estuary (McAlister et al., 2006) was recently upgraded to 3D by BMT_WBM and is available on a fee-for-service basis.

2.7 Long-term evolution of estuaries

The concept of equilibrium is fundamental to top-down and regime type models but it is questionable whether equilibrium ever exists. Variability in forcing parameters such as sea-level, river flows, storm surges etc. force changes to the equilibrium state and equilibrium is best considered as being dynamic in nature. Whether an estuary would ever in-fill completely is a moot point as forcing parameters rarely remain constant over a sufficiently lengthy period. Examples of in-fill and morphological change over many decades usually trace from anthropogenic influences. For example, in 1637 Cley-on-sea was a small fishing village on the Norfolk coast of the UK with an estuary sufficiently large for use by fishing and trading vessels. The estuary was canalised so that tidal flats could be used for agriculture resulting in excessive silting of the estuary. The local fishing boat owners protested but to no avail (Cozens-Hardy, 1924):-

> ***"The banke of earth . . . taketh away . . . the indraught of water 80 rodds and upwards in breadth and one myle at least in length [an area larger than 65 ha] . . . so that what sylt or mudd the flood tide bringeth in doth settle and remaine in the navigable channel . . . through want of the ebb tide which formely overflowed the aforesaid 80 rodds of ground in breadth and one myle in length"***

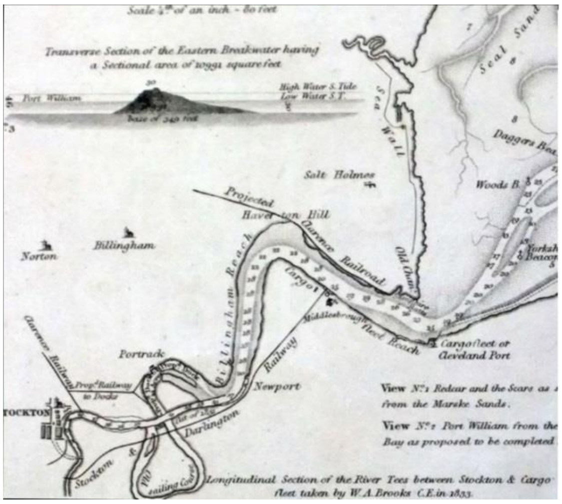
Today the old port is about 9 km upstream from the Norfolk coast (about 1.5 km in a direct line) with a channel shrunken to a few metres in width (Fig 1.8a) Exacerbating the problem is a small barrage across the estuary (Fig 1.8b). The tidal levees are 200 to 300 m apart giving an indication of the width of the estuary in the 1600s.

Fig. 1.8 The old port of Cley Norfolk (a) what remains of the estaury and (b) a small barrage upstream of the old port. Photos I Kidd

The River Tees estuary (Fig. 1.9) on the border of County Durham and Yorkshire UK has undergone anthropogenic alteration for centuries. Maps dating from the 1600s show Middleborough on the coast and a highly sinuous river course. The river was an important transport artery and the meandering system was not efficient for that purpose. Today Middleborough is 12 km upstream of the mouth and sinuosity of the Tees is reduced by removal of meanders and canalisation. The main entrance channel is extensively dredged and restricted with training walls and breakwaters. The system is barraged at Middlesbrough forming a headpond to Low Moor confined by (what were once tidal) levees stretching over 20 km upstream.

(a)

(b)



(c)

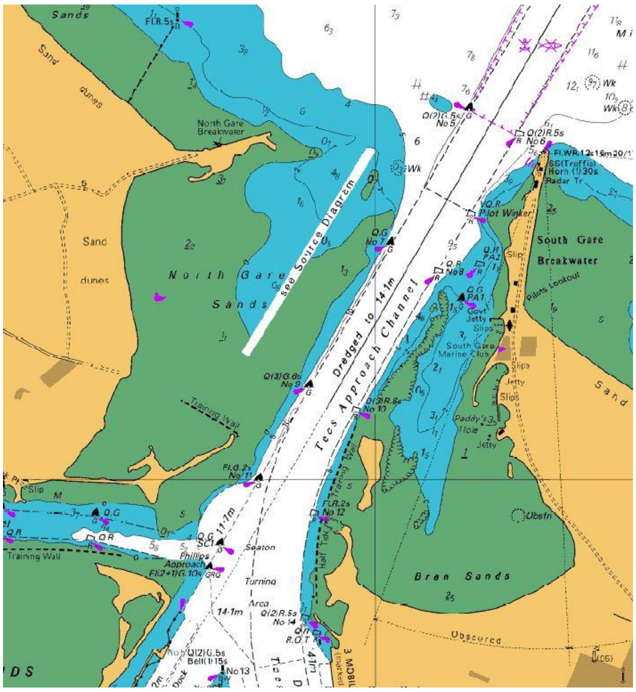


Fig. 1.9 The River Tees and surrounds (a) in 1610; (b) a map from 1830s and (c) present day navigation chart showing dredged areas. (a) and (b) sourced (Genmaps, 2015); (c) sourced British Admiralty Chart 2566

2.8 Problem estuaries and remediation projects

The impetus for estuarine recovery programs is largely the deterioration of ecosystems (Borja et al., 2010; Duarte et al., 2014), partly morphological but mostly due to increased input of pollutants, organic matter, nutrients, sediments and physical disturbance through construction and fishing. In the USA the non-regulatory National Estuary Program (NEP) works ***"to improve the waters, habitats and living resources of 28 estuaries across the country"*** (https://www.epa.gov/nep accessed July 2016). Projects span the east and west coasts and Puerto Rico (Fig. 1.10). In the late 2000s restoration of rivers lakes and estuaries was a two $billion per year industry in the USA with 64 dams removed in 2008 (Duda et al., 2011), (http://www.water.ca.gov/fishpassage/docs/dams/dams08.pdf accessed July 2016)

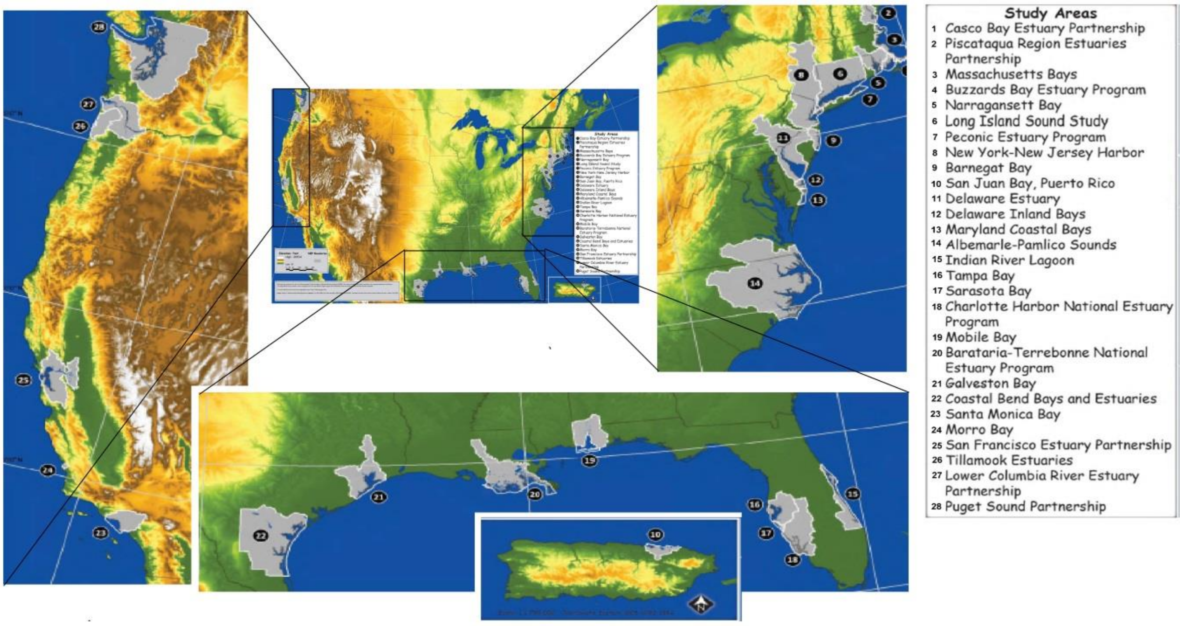


Fig. 1.10 Estuarine restoration projects around the USA sponsored by NEP. Source (https://www.epa.gov/nep accessed July 2016)

Restoration of the Petitcodiac River in New Brunswick Canada by opening of the Moncton Barrage in 2010 is described previously. The project was a finalist in the *Theiss International River Prize* of 2013. Professor David Suzuki described the barraging of the river (http://www.davidsuzuki.org/blogs/science-matters/2010/04/watching-the-petitcodiac-river-flow---once-again/ accessed July 2106):-

"It's hard to imagine that people once thought blocking a river in such a way was a good idea. It's another example of how we humans often act without enough knowledge to fully understand what the consequences of our actions will be".

The Australian scenario is described in ***Estuaries of Australia in 2050 and Beyond*** (Wolanski, 2014) in which estuaries are divided into three groups; pristine, in process of degradation, and degraded by anthropogenic stressors. The latter include the Tamar River, Port Jackson, Port Phillip and the Murray River/Coorong.

3. The Tamar River estuary

The upper Tamar was first settled by Europeans in 1806 (Lee, 2003) and so degradation has been relatively recent. Anthropogenic change has occurred in European estuaries for millennia (Morris and Mitchell, 2013) and the ancient Egyptians controlled the Nile and the Nile delta with levees, canals and catch basins (Wilson, 2013). The natural state of these systems and what the path of natural evolution would have been is unclear, although for the UK and Europe, rudimentary maps exist pre-dating the 1600s, whereas maps (Scott, 1837; Welsh, 1830) and written descriptions (Lee, 2003) of the Tamar in the early 1800s provide a reasonably clear picture. A description of the upper Tamar River estuary is provided at Appendix A (Davis and Kidd, 2012) and Appendix C (Kidd and Davis, 2015) which includes an abridged account by William Collins (Lee, 2003). On the 4th of January 1804 Lt. Col. William Paterson anchored his ship *Lady Nelson* 1.5 miles south of Tamar Island and the crew explored the upper estuary in the ship's dinghy. William Collins describes the North Esk…,

'…***the water is perfectly fresh and good…..it runs through low marshy country which appears at times to be overflowed. The soil on its banks is very good, and there is a great extent of it.'***

;…and the Cataract Gorge,

'***...I observed a large fall of water over rocks, nearly a quarter of a mile up a straight gully, between perpendicular rocks nearly 150 feet high; the beauty of the scene is probably not surpassed in the world; this great waterfall or cataract is most likely one of the greatest source of this beautiful river, every part of which abounds with swans, ducks and other kinds of wildfowl.'***

An early navigation chart (Welsh, 1830) is often rejected by scholars for lack of detailed bathymetry (Fig. 1.11). However, the chart contains detailed tidal information and Welsh calculated the longitude at Low Head as 146^0 49' E (the actual longitude is 146^0 47.2' E), whereas a commonly cited version updated by Commander Stokes and published by the Hydrographical Office in 1870 is slightly more accurate (146^0 48.25' E). A map published in 1832 shows the extent of intertidal areas in the upper estuary (Fig. 1.12)

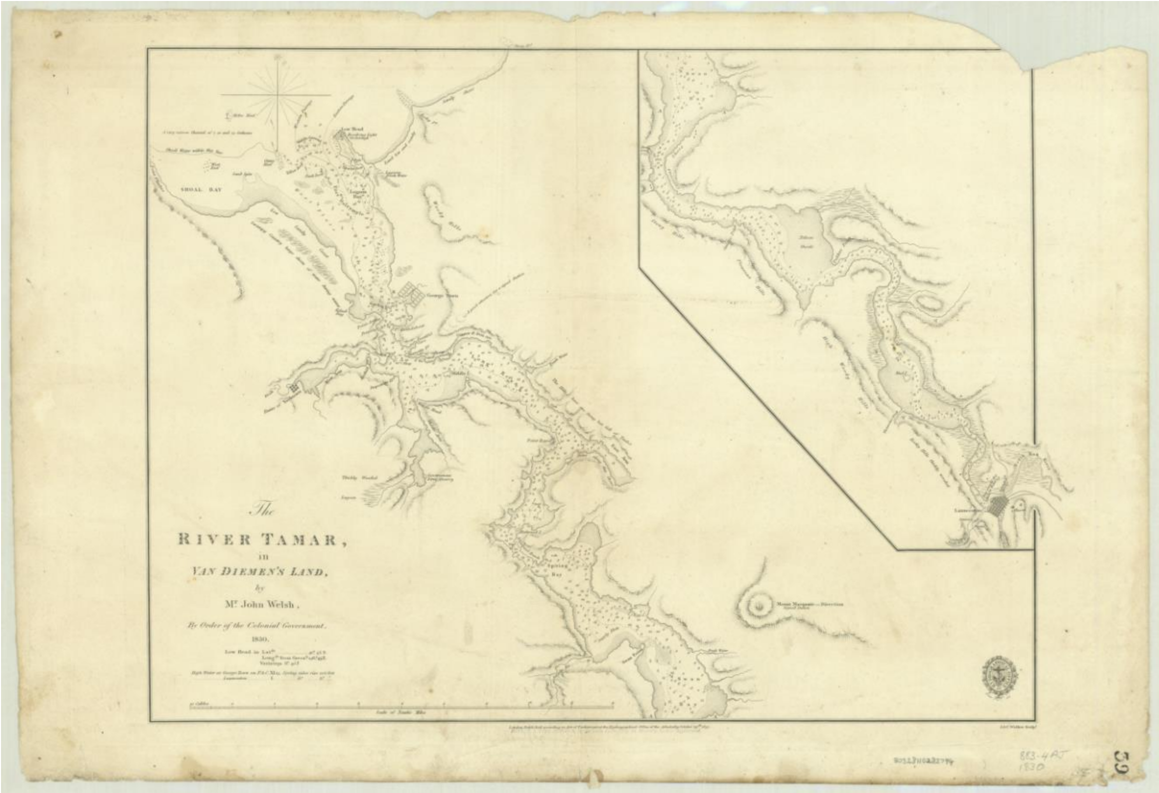


Fig. 1.11 Navigation chart of the River Tamar (1830); source (Welsh, 1830)

Fig. 1.12 Map (Ross and Bock, 1832) showing extensive areas of intertidal flats and evidence of early canalisation of the North Esk River estuary (Clergyman's Glebe is dry despite being below MHWL)

3.1 The present state

Much of the estuary shown in Fig. 1.13 is now canalised with tidal and flood levees preventing semi-diurnal inundation of old tidal flats (Fig. 1.12). Tidal levees run from opposite the Tailrace to Henry St. Bridge. The flow of the South Esk River (bottom left) is now mostly redirected to the Tailrace (top left) and the tidal flats of Invermay and Inveresk are highly urbanized. The North Esk River is tidal over almost 12 km (beyond bottom right of Fig. 1.13) and is the natural extension of the Tamar River estuary.

Fig. 1.13 Satellite image of Launceston and the upper Tamar River estuary (source Google earth)

3.2 The dynamic nature of the silt accretion

Prior to 2013 silt reductions in the Yacht Basin were due to dredging and flood events but silt returned at >10,000 m^3 per month (Fig 1.14). The raking program of 2013 moved ~ 140,000 m^3 from the Yacht Basin although this was accompanied by five high flow events. Fig. 1.14 provides graphical evidence of the ineffectiveness of dredging and raking when compared to natural forcing.

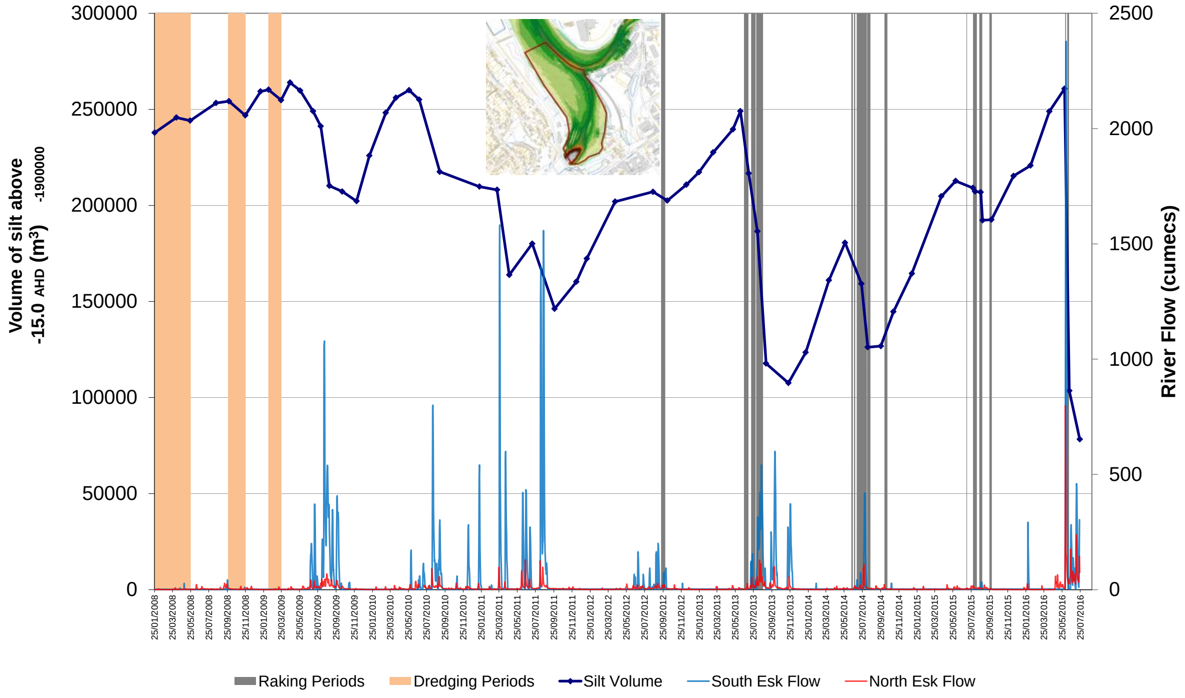


Fig. 1.14 Silt volumes in Home Reach since raking commenced in 2013. The maximum volume at equilibrium is < 2,180,000 m^3 above -15m Australian Height Datum (AHD). Dredging in 2008-2009 and intense raking in 2014 moved less silt than the high flow events of 2013 and June 2016. (Data courtesy of LFA)

Historically the silt accretion of the upper estuary waxed and waned with the discharge of the South Esk River, and the system was in a state of dynamic equilibrium (see Chapter 2).

3.3 Some fundamental observations

This study is predicated on several observations, which may seem trivial, but are novel approaches, fundamental to the issue and are not mentioned in any previous study or report. They represent a paradigm change in the methodology for tackling the problems of the upper Tamar River estuary. For a simple system composed of two elements, water and silt, the corollary of '*too much silt*' is '*not enough water*'. The volume of silt and the volume of water at mean high water level (MHWL) are mutually exclusive or in a 1:1 zero sum game (Fig. 1.15). Dennis et al. (2000) described this in terms of processes,

"***the basic 'rule' (is) that reductions in tidal volume lead to sedimentation and vice versa***",

but stopped short of recognising the mutual exclusivity of the volumes. This leads to a second observation; any change in tidal volume equates to the same change to silt volume over the intertidal banks (provided the tidal range remains constant). The intertidal banks are exposed at low tide and excessive silt accretion on the banks is considered unsightly and a loss of physical and visual amenity. Changes to the tidal prism are therefore a useful metric for evaluation of changes to the amenity and ecosystem services provided by the estuary. In Chapter 3 a method for the calculation of the tidal prism is developed from the geometry of the estuary and the tidal range and used as the basis for a first order morphological response model (FORM) (Kidd et al., 2016a).

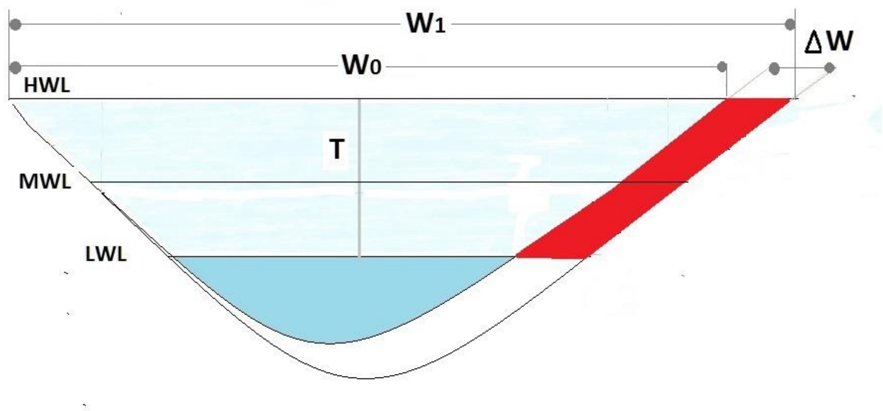


Fig. 1.15 The volume of silt at mean high water level (HWL) is mutually exclusive with the water volume (tidal prism). Any change to the tidal prism equates to the same change in silt volume on the intertidal banks (red shading). Some tidal volume will seep into the intertidal banks but for cohesive sediments this volume should be small. MWL is mean water level, LWL is (mean) low water level, *w* is width and *T* is tidal range

A change in tidal prism will also produce a change in silt volume below mean low water level (MLWL). In Chapter 5 a method is presented for calculating this volume between two stations.

3.4 Previous studies

Studies into the silt accretion issue in the upper Tamar have been conducted over the last 130 years (Foster and Nittim, 1987), with other peer reviewed studies into rice grass (Sheehan and Ellison, 2004; Sheehan and Ellison, 2014), flooding (Atkins and Vince, 2009), silt accretion (Davis and Kidd, 2012), catchment (watershed) and runoff issues (Peel et al., 2003), and pollution and sewage (Seen et al., 2004). Foster et al. (1986) cited consultant's reports dating from 1882 (Table 1.2)

Table 1.2 A list of reports commissioned on the Tamar River cited by Foster et al. (1986)

Year	Report	Author
1882	River Tamar and the Port of Launceston	C. Napier-Bell
1890, 1899	Tamar River Improvements	C. Napier-Bell
1910	Interim Report of Committee on River Improvement Scheme	
1914	Port of Launceston Improvement Scheme	W. H. Hunter
1916	Report of Royal Commission on River Tamar	
1938	Report on Improvement of the Upper Reaches of the Tamar River	Gutteridge and Gillean
1947	Report on Tidal Model of River Tamar Tasmania	T. A. Lang
1961	Report on the Tamar Estuary	T. E. Emmett

Reports concentrated on dredging and works on the channel with the aim of improving navigation. More reports have been commissioned since 1986 (Table 1.3).

Table 1.3 Reports commissioned since 1986

Year	Report	Author
1997	State of the Tamar Estuary – A review of Environmental Quality Data to 1997	Pirzl and Coughanowr
2006	Future for the Tamar Basin	Professor Brian Jones, University of Wollongong
2008	Tamar Estuary Review of Foster (1986) Report on Sedimentation Processes	BMT_WBM
2009	Sediment Evaluation Study Report – volume 1	GHD
2009	Sediment Evaluation Study Report - volume 2	GHD
2009	Report for Upper Tamar River Siltation Study - Preliminary Options Analysis	GHD
2009	Report for Tamar Siltation Project - Stakeholder Engagement Outcomes Paper	GHD
2009	Cataract Gorge Environmental Flow Review; Cataract Gorge Workshop Summary Report	Hydro-Electric Corporation (HEC)
2009	Management of the Tamar Estuary and Esk Rivers - Legislative Council report	Finch, Dean and Wing
2015	Tracer Analysis of Sediment Redistribution of Tamar Estuary for Launceston Flood Authority	AMC Search and ETS Worldwide Ltd

3.5 Identification of problem, symptoms, causes and root-causes

The excessive silt accretion in the upper Tamar estuary clearly causes problems such as loss of amenity and health issues but the delineation of symptoms, causes, and root-causes is not trivial. Consultants' reports have been commissioned and written on the assumption that the silt is the sole (and root-) cause of the amenity problem; sources, properties and movement of silt have been analysed without providing clear solutions. Suggested solutions were either not sustainable (i.e. they required on-going maintenance or intervention), or produced unsatisfactory trade-offs. Compounding the problem was the on-going dredging of the upper estuary throughout the 20th century, which maintained a state above equilibrium to allow larger ships to berth at King's Wharf in Home Reach than were previously able. Without a clear methodology or intent to identify root-causes most problems will remain unsolved. The Foster report for instance (Foster and Nittim, 1987; Foster et al., 1986) was a comprehensive and professional study purportedly into

"*…the causes of siltation in the Tamar River and to examine methods to overcome or mitigate the problem*",

but was effectively a study into the properties sources and movement of silt and the most cost effective means of maintaining the equilibrium imbalance caused by dredging. The report failed to identify excessive silt accretion as a symptom of an underlying root-cause and ignored the influence of the North Esk River despite it being a continuation of the main estuarine channel (Davis and Kidd, 2012). A review in the 2000s (BMT_WBM, 2008) found the Foster *et al.* report to be accurate but again offered no sustainable solutions. By then dredging had all but ceased due to cost and problems relating to spoil disposal and the estuary was returning to an equilibrium position much smaller than publically acceptable (Ellison and Sheehan, 2014) and smaller than in 1806 (Davis and Kidd, 2012). Sediment raking was conducted in the upper estuary in the winter months of 2013, 2014, 2015 and 2016 to remove sediment and restore some amenity. In a bid to discover the fate of raked sediments a tracer study was conducted in 2015 by AMC Search and ETS Worldwide Limited. The subsequent report was critical of both the reports of Foster and BMT_WBM. However, it too was a report into the symptom of the problem and confirmed that raking did not remove sediment from the estuary and therefore was not a viable permanent solution to excessive silt accretion. In the penultimate draft of the report the authors recommended:

"Along with key stakeholders, LFA should commission a study by a suitably qualified company, group or individual, familiar with estuaries, to carry out a detailed and comprehensive scientific review of all the available data (including bathymetry data),

reports and modelling analysis in order to build a comprehensive understanding of estuarine morphodynamics, siltation and dredging."

The recommendation is effectively a further study into the symptom of the problem and was removed from the final draft. Nevertheless, the failed old paradigm prevails (that silt is the problem) (Davis and Kidd, 2012) which assumes a solution can be found from a greater understanding of the symptom rather than an attempt to ascertain and remove the root-causes. Root-cause analysis is further discussed at Appendix D.

3.6 Datasets

The preliminary stages of this research identified inconsistencies in some datasets which had been used in various reports and papers pertaining to the Tamar River and surrounds. They are discussed in paper #6 (Appendix B) which was presented as a research note to, and published by the journal *Natural Resources* (Kidd et al., 2014)[1]. In particular, the study identified the high variability of tidal datasets and stressed the need for sampling over long time spans for tidal information. Errors were found with the tidal gauge datum used by the Bureau of Meteorology at Low Head and with a publically available digital elevation model (DEM) (theLIST, 2014) for the Launceston area. The 2015 tracer study report also mentioned the unreliability of commonly used data sets:-

"Measurements and data collected by Foster et al., (1986) do not appear to have been made simultaneously with other key synoptic data leading to confusing and often contradictory conclusions and, based on knowledge of physical processes in estuaries in the late 1980's, possibly highlighting limited understanding of estuarine processes and sediment transport in estuaries. This has been further compounded by use and acceptance of the data reported by Foster et al. in subsequent reports, and modelling in some cases, without adequate scrutiny or cross-referencing to a significant number of publications from the 1960's to the present time, on this subject matter."

3.7 Tidal asymmetry in the upper Tamar

The results of paper #1 (Chapter 2) confirm a similar phenomenon in the Tamar River estuary to that in the Petitcodiac River, flood biased velocity asymmetry and an unbiased sediment flux, but with a much less time differential between flood and ebb duration

[1] Paper #6 is not presented in the body of this thesis as it was not peer reviewed prior to publication.

(approximately half an hour to an hour). Asymmetry of tidal velocity was found to increase as regime is approached although net sediment flux tended to zero, despite the duration of the flood tide remaining less than the duration of the ebb tide. Asymmetrical tides, in particular flood dominant tides, have been incorrectly cited as the cause of the excessive silt accretion (Foster and Nittim, 1987), giving rise to strategies to reduce their influence. Proposals have included barrages at several different locations, realignment of the North Esk River and in-stream tidal energy turbines. At the present time proponents of a barrage at Long Reach in the lower Tamar River estuary (Tamar Lake Inc. http://tamarlake.com.au/) have a high public profile, although a peer review of the environmental consequences of the barrage was not positive (Rissik, 2014). Another barrage across the North Esk River was proposed by the Launceston Flood Authority (LFA) (Examiner 2013a) with the express aim of stopping asymmetrical tides (see Chapter 6 for modelling). The proposal has been mothballed while the LFA concentrate on silt raking as their preferred option for silt management. Another barrage proposal received some prominence around 2000. In this, the Lake Batman proposal (Fig. 1.16) the tidal North Esk River was re-routed to Stevenson's Bend and a freshwater lake created in Home Reach. The plan was rejected by the local council as being too expensive at >>AU$600,000,000 (Pers. Comm.)

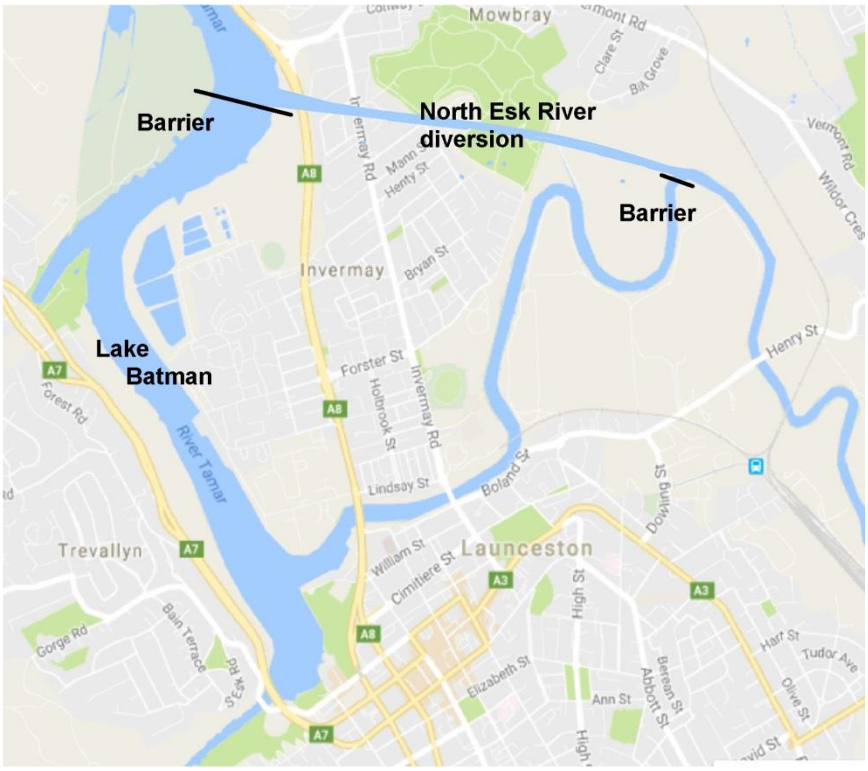


Fig. 1.16 The Lake Batman project, was rejected as being too expensive

In Chapters 4, 5 and 6 the ramifications of these and other barrage proposals are discussed. It is clear that none address the root-causes of the excessive accretion and that trade-offs and ecological surprises can be expected (Gordon et al., 2008). PIANC (2011) summarise the prognosis for any project as,

"working with nature gives a good chance of success; working against nature guarantees failure".

Stopping the tidal flow with a barrage is a clear example of working against nature and the negative impacts can be severe. The morphological impact of the Lake Batman proposal for example, is demonstrated by a simple application of FORM (see Fig. E1). The tidal prism at the new confluence of North Esk and Tamar Rivers is approximately 1,000,000 m^3 compared with over 4,000,000 m^3 presently.

4. Hypothesis

Greek mythology provides an apt metaphor for the hypothesis of this thesis. ***The fifth labour of Heracles*** tells of how Heracles cleaned the Augean stables in one day (Ruck and Staples, 1994) by re-routing the rivers Alpheus and Peneus; a classic example of ***working with nature*** (PIANC, 2011). In paper #5 (Chapter 6) strategies are presented which provide for sustainable remediation of the silt accretion issue. The recurring theme of the recommended strategies is an increase in the water flow, either estuarine or freshwater, to flush sediments from the system and partly reversing the anthropogenic changes of the last 200 years.

The concept of increasing the tidal flow is not new as the examples of Cley and the Petitcodiac attest, and the idea was raised locally in c1928, in the following (excerpt of a) letter published by the local newspaper (The Examiner).

"Siltage in the Tamar

(To the Editor)

Sir,-

………The origin of the deterioration of the upper reaches was the reclamation of the large spill areas which existed in former days at and near the head of the river. This I am quite certain of, as I have personally seen the same thing occur in India on the Bididhari River, which in its upper

reaches silted up to practically nothing, but became a different river, with a deep channel, within 12 months of the opening out of a new spill area at its head, …………………

Another factor which has expedited the deterioration of the upper reaches is the dumping of dredgings on the adjacent soft banks, as the great weight of spoil is slowly, but surely, squeezing the soil into the river and narrowing the channel. –

Yours, etc

W. B. MacCabe M. Inst. C. E. (Member of the Institute of Civil Engineers)"

Despite Mr MacCabe's advice, management of the upper Tamar River continues to this day using the same failed paradigm identified by Davis and Kidd (2012), i.e. maintain the amenity by removing the symptom of the problem. The words of Mr MacCabe and the mythological efforts of Heracles provide a basis for the hypothesis of this thesis which will hopefully be the catalyst for a new scientifically based managerial paradigm which sees the upper Tamar River estuary restored and rejuvenated, so that once again, in the words of William Collins (1806), "***the beauty of the scene is probably not surpassed in the world"*** (Lee, 2003).

5. Methodology of this thesis

The study conducted by Davis and Kidd (2012) of the upper Tamar River estuary identified the causes of the excessive accretion of silt which had occurred since European settlement in 1806. That paper, (Appendix A) considered the changes to the forcing parameters acting on the upper estuary and concluded that the bathymetric changes were caused by locally introduced anthropogenic stressors. In particular, the study identified a reduction in tidal prism and reduced freshwater flows as the main stressors responsible for the excessive siltation. This thesis extends the work of Davis and Kidd (2012) on the upper Tamar River estuary by:-

a. evaluating the role of tidal asymmetry in morphological change,

b. developing a simple regime model (FORM) and applying it to the past and present morphologies,

c. assessing the suitability of a TEB to mitigate sea-level rise in vulnerable estuaries, including the upper Tamar River estuary,

d. predicting the future morphology of the Tamar River estuary resulting from various remediation strategies and

e. where appropriate, making comparisons with international examples.

The conclusions emanating from this thesis are applicable to many similarly degraded coastal-plain estuaries (see above) around the globe.

5.1 Thesis structure

This thesis is structured (Fig 1.17) around seven papers either published or in peer review (Table 1.4), six of which were written during the period of candidacy. Paper #6 is not included in the body of the thesis as peer review was post publication. Nevertheless it was the starting point for this study and was a review of datasets relevant to the hydrology and dynamics of the Tamar River estuary and is included at Appendix B. Appendix C is a magazine article written and published during candidacy giving a layman's summary of the Davis and Kidd (2012) paper, including a chronology of events leading to the present degradation. Appendix D is included as a complementary aside to the study of Davis and Kidd (2012) and highlights management shortcomings and the ensuing paradigm when a problem is not clearly defined. Appendix E (not shown in Fig. 1.17) is the application of FORM to the Lake Batman Project. Appendix F is a GIS project conducted during candidacy on the threat of sea-level rise on the infrastructure of Launceston.

Table 1.4. Summary of aims and hypotheses for each chapter

Chapter & Title	Aim	Hypothesis	Rationale for study	Importance
Chapter Two Equilibrium imbalance due to sediment raking influences M2 tidal constituent, M4 and M6 harmonics, tidal asymmetry and net sediment flux	To determine the reaction of M2, M4 and M6 tidal constituents to a forced change in equilibrium status and predict the interaction at equilibrium when net sediment flux is zero	That post raking; (a) the M4-induced asymmetry causes spatial settling lag (SSL) which dominates any M6-induced Temporal settling lag (TSL), (b) M4 is affected by the removal and reformation of tidal flats; (c) the interaction of M2 with M6 increases channel depth as equilibrium is approached; (d) changes to θ_{M6} and θ_{M4} are subtle; θ_{M6} increases towards its angle of greatest influence whereas θ_{M4} increases away from its angle of greatest influence and (e) flood and ebb maximum velocities increase as equilibrium is approached	Asymmetric tides have been blamed for degradation of upper estuary. The annual raking program provided the opportunity to study a system as regime was anthropogenically disturbed and naturally restored. No such studies were found in the literature	This study informs the management of silt removal locally and in general. Locally asymmetrical tides are not well understood and management needs to refocus on stressors acting to degrade the estuary
Chapter Three A First-Order Morphological	To develop a simple regime model applicable in coastal	(a) that the geometry of an estuary could be accurately modelled (Figure	The genesis of FORM is Davis and Kidd (2012) who	The concept of bathymetric migration is not mentioned in

Response Model (FORM) for predicting hydrologically induced bathymetric change in Coastal-plain estuaries	plain estuaries for modelling the bathymetry according to certain forcing parameters	3.1, regime state 1) by combining regime theory with a site-specific tidal prism equation expressed as a function of distance from the head and a width equation (b) the model could be used to predict the bathymetric outcome (width and tidal prism) (Figure 3.1, regime state 2) emanating from an anthropogenic adjustment of the tidal prism	recognised bathymetric migration within the tidal North Esk River. FORM expands on that idea to calculate tidal prisms at any point downstream of the head noting that tidal prism is covariant with the width of the channel. FORM is central to this thesis and all subsequent chapters use it to some extent	the literature and has relevance in identifying systems which are transitioning from one regime to another. FORM extends the applicability of other regime models to include multi-tributary systems and multiple intertidal storages
Chapter Four A scenario-based approach to evaluating potential environmental outcomes following a tidal barrage installation	To assess the different ecological and morphological impacts of five putative total exclusion barrages in the Tamar River estuary	That the impacts of a barrage on estuarine hydrology, morphology and ecology in the Tamar River estuary would vary with the distance of the installation from the mouth	TEBs are known to cause ecological and morphological problems. Despite evidence from existing installations, TEBs of various guises continue to be presented as viable options for the Tamar River; to solve the silt accretion problem, and to stop asymmetrical tides which are also (erroneously) seen as problematic	It is important that the full ecological and morphological ramifications of TEBs are understood. These effects are hidden in many existing installations by dredging and other management practices. Numerical models do not work over sufficiently long time scales to adequately model the morphological impacts and a regime model is required.

Chapter Five Total exclusion barrages as sea-level rise mitigators: The geomorphological trade-offs for new installations	To assess whether the benefits of mitigating against sea-level rise would be out-weighed by the trade-offs associated with a total exclusion barrage in the Tamar River	That the existing structures provide differing levels of protection and that none provide justification for a TEB in the Tamar River estuary.	This chapter forms the basis of a talk given by me at ECSA55 conference in London in September 2015. The paper brings together the concepts of bathymetric migration, degradation of estuaries and mitigation of sea-level rise.	Sea-level rise is a looming threat to all coastal communities especially those with urbanisation below present sea-level. Launceston is particularly at risk with ~ 4 km^2 below MHWL. Effective mitigation requires more than knee-jerk reactions such as TEBs..
Chapter Six Bathymetric rejuvenation strategies for morphologically degraded estuaries	The aim was to identify those strategies having a high probability of success, whilst identifying trade-offs of other proposals which do not address the known stressors. Implications for asymmetrical tides, existing storages and other ecosystem services are considered	That those strategies which reduce, mitigate or remove known stressors will be sustainable, whereas those which add to the stressors will have negative impacts. Partial restoration of the estuary is possible	Consideration of rejuvenation strategies for the Tamar is the culmination of preceding chapters of this thesis. Previously suggested strategies were based on a failed paradigm and a scientifically based approach was/is required.	The importance of a scientific approach to addressing the problems beguiling the upper Tamar cannot be understated. The strategies presented have applicability in other similarly degraded estuaries elsewhere

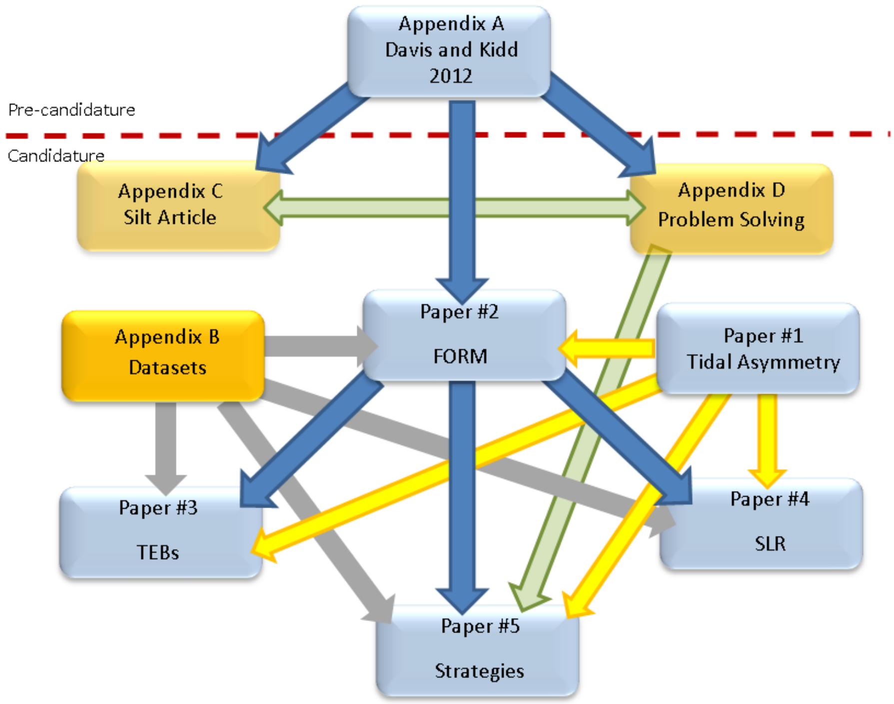


Fig. 1.17 A conceptual framework of the thesis; papers were not published in chapter order

Conceptually, the thesis can be divided into three phases; Appendices A, B, C, D and Chapter 2 represent the first phase in which existing data sources are assessed for accuracy, suitability and usefulness and deficiencies identified. One deficiency was the lack of a reliable long term tidal dataset which was subsequently gathered, resulting in Paper #1. This informed an understanding of how the hydrodynamic processes affected the sediment dynamics within the upper Tamar. These processes act under the influence of forcing factors such as flow rates, tidal prism changes and sea-level rise, to alter the morphodynamic equilibrium of the estuary from one state to another.

This change in state of equilibrium is the premise for the second phase of the thesis which builds on the knowledge gained from phase 1 and results in the formulation of the First Order Morphological Response Model (FORM) used in subsequent chapters (phase 3). FORM is developed in Chapter 3 and models the present bathymetry of coastal-plain estuaries and the resultant bathymetry following a permanent change to a forcing parameter.

FORM is central to phase three of the thesis. In Chapter 4 the impact of five putative total exclusion barrages (TEBs) in the Tamar River estuary are discussed using FORM to assess the morphological implications of each installation . This topic is included as TEBs have been suggested for the Tamar over many years and various studies have recommended their installation. Chapter 5 introduces the ramifications and mitigation of future sea-level rise for the Tamar. Four international examples are discussed where existing TEBs provide some mitigation of SLR. The concept of bathymetric migration, central to the FORM model, is extrapolated to the case of rias to provide a qualitative assessment of the impact of TEBs and the morphological trade-offs as SLR mitigators. In Chapter 6 findings from each preceding chapter combine to present and analyse possible remediating strategies for the silt accretion problem in the Tamar River and in a general sense, to similarly degraded estuaries around the globe.

5.2 Precision and accuracy of data

The level of accuracy and precision of data presented in this thesis are generally presented as generated by the relevant software and this has been rounded down to fewer decimal places where applicable. The data and accuracy thereof are presented to the satisfaction of the journals concerned, in which there is (/appears to be) an unwritten rule that such calculations represent order of magnitude accuracy or in the words of one examiner of this thesis, "back of the envelope calculations". Whilst every effort was made to keep errors to better than order of magnitude (unless specifically stated), calculated results should be viewed as approximate in all cases. Google Earth has been almost exclusively used to collect width and length measurements and its' limitations are described as:-

"Google makes no claims as to the accuracy of the coordinates in Google Earth. These are provided for entertainment only and should not be used for any navigational or other purpose requiring any accuracy whatsoever.

Our imagery varies from sub-meter resolution in major cities to 15 meter resolution for most of the earth's surface, with a global base resolution of 1KM. Since our database is constantly being updated, we cannot state a specific resolution for any geographic region.

Google acquires imagery from many different sources with many different file formats, projections and spectral characteristics. All imagery sources are fused into a single global database with a proprietary format that has been developed for the specific purpose of streaming to our client software." (https://productforums.google.com/forum/ accessed 4/3/2017).

Sampling from Google Earth was of the high water level which is usually visible and obvious from the image although the tide stage could be lower. High water levels from previous equilibrium states are also visible in some images and are used in the case of the Petitcodiac for example. In this thesis, sampling is assumed to be accurate to within ±2 meters for narrow estuarine sections* to ±5 meters for wider sections, bearing in mind that the ultimate aim is to calculate tidal prism volumes, which are usually stipulated in volumes $\pm10^5$ m^3 or at the mouth of large estuaries possibly $\pm$ 10^9 m^3; so a high level of precision is not paramount at the data acquisition stage. Accuracy of other instruments such as sonar loggers are mentioned where applicable and error bars are used in relevant data plots.

*error will be affected by the zoom applied to the image

CHAPTER 2:

EQUILIBRIUM IMBALANCE DUE TO SEDIMENT RAKING INFLUENCES M2 TIDAL CONSTITUENT, M4 AND M6 HARMONICS, TIDAL ASYMMETRY AND NET SEDIMENT FLUX

Abstract

Statistical correlations are analysed with a simple sediment dynamics model to ascertain causal links between tidal constituents and net sediment flux as the upper Tamar River estuary in Tasmania, Australia returns to equilibrium following an annual program of sediment raking. Raking temporarily displaces ~ 200,000 m^3 of sediment downstream, partly in-filling the channel and placing the system out of equilibrium, which reacts with a returning flood sediment flux building steadily before the next raking season. Sea-surface-elevation (SSE) data and tidal velocity data were collected over 22 and 4 months, respectively, and two monthly means of SSE constituent amplitudes and relative phases for M2, M4 and M6 were extracted. The SSE of M6 (A_{M6}) is significantly $>A_{M4}$ and the velocity of M6 (u_{M6}) was up to three times that of u_{M4}. A principal component analysis (PCA) of constituent amplitudes, relative phase angles and monthly silt volume changes (ΔV) shows that, the phase of the M2 SSE constituent (θ_{M2}), the relative phase of M4 harmonic (θ_{M2}-$\theta_{M4}/2$) and the vector sum $(\overline{\mathrm{M4}} + \overline{\mathrm{M6}})/\mathrm{M2}$ were correlated with the changing silt volume (ΔV). A_{M2} influences A_{M6}, θ_{M2}-$\theta_{M4}/2$ and θ_{M2}-$\theta_{M6}/3$ through the neap-flood cycle and annual/long-term signals. A_{M2} was correlated with ebb sediment flux, θ_{M2}-$\theta_{M4}/2$ is correlated with flood-biased sediment flux and θ_{M2}-$\theta_{M6}/3$ is correlated with negative values of ΔV. High velocities before and after low tide, scour the channel and provide the mechanism for transport of sediment from the channel to the intertidal banks as equilibrium is restored. Equilibrium was not re-established during this study, however the flood-biased velocity caused by M4, strong ebb-currents caused by M6, dwells at high and low water (caused by $\overline{\mathrm{M4}} + \overline{\mathrm{M6}}$), lag and other processes affecting sediment dynamics must ultimately balance for zero net sediment flux.

Keywords

Sediment distribution; tidal constituents; sediment flux; estuary; harmonic analysis; Australia, Tasmania, Tamar River estuary

1. Introduction

This study examines asymmetries and feedbacks between tidal and sediment dynamics during transitions in and out of equilibrium as a consequence of anthropogenic perturbations (sediment raking). The interplay of estuarine bathymetry, tidal dynamics, sediment dynamics and net sediment-flux involves strong feedbacks (De Swart and Zimmerman, 2009). Under the influences of friction, channel convergence and hypsometry, the sinusoidal M2 wave becomes distorted as it propagates through an estuary. The distorted wave represents the transfer of energy from M2 to the M4, M6 and possibly M8 harmonics (Fig. 2.1). The link between bathymetry and tidal dynamics is well understood (Amin, 1993; Aubrey and Speer, 1985; Blanton et al., 2002; Boon and Byrne, 1981; Cartwright and Amin, 1986; De Swart and Zimmerman, 2009; Dronkers, 1986; Dronkers, 2013; Dyer, 1986; Friedrichs and Aubrey, 1988; Postma, 1954; Speer and Aubrey, 1985; Van de Kreeke and Robaczewska, 1993; Van Maren and Winterwerp, 2013). The dominant mechanisms which cause asymmetry vary from estuary to estuary and sediment dynamics react non-linearly (and possibly feedback) to tidal dynamics due to various effects including, lag (Dyer, 1997; Van Maren and Winterwerp, 2013), mixing (MacCready, 1999), wind waves (Dronkers, 1986; Fagherazzi et al., 2007), density differences and internal tides (Jay and Musiak, 1996; Jay and Musiak, 1994), Coriolis forces (Huijts et al., 2006), asymmetries in water depth (Chernetsky et al., 2010), river discharge (Bourman and Barnett, 1995; Leonardi et al., 2015), turbulence induced flocculation (Winterwerp, 2011), etc.. Furthermore sediment transport is proportional to the 3rd power of current velocity (u^3) (Wright et al., 1999), and therefore linking tidal dynamics with bathymetric change is problematic and a model of sediment dynamics is required.

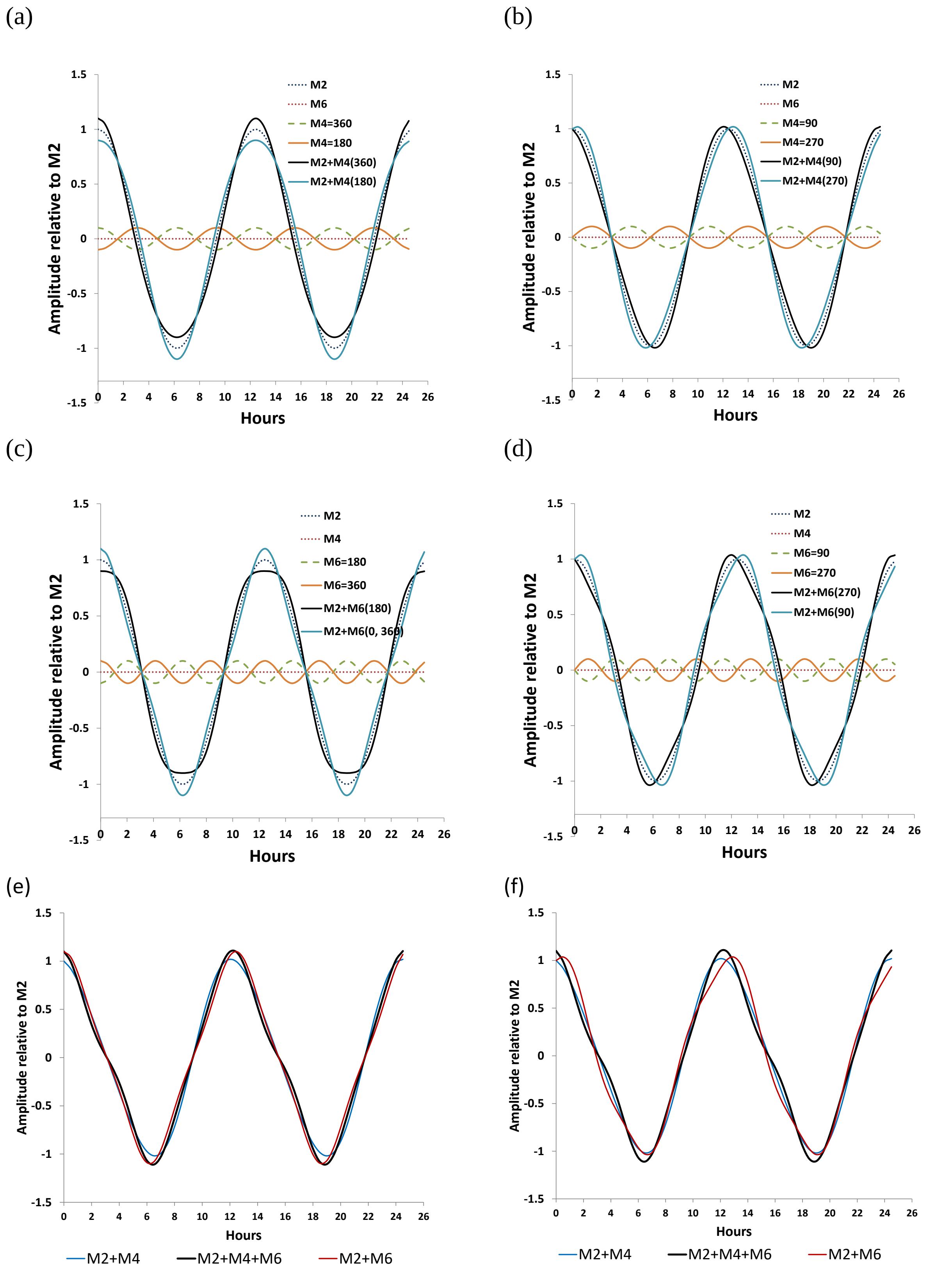


Fig 2.1 Hypothetical examples of maximum sea-surface-elevation (SSE) distortion caused by various relative phase angles of M4 ($2*\theta_{M2}-\theta_{M4}$) and M6 ($3*\theta_{M2}-\theta_{M6}$) when

combined with M2 ($\theta_{M2} = 0^0$) for; (a) for $2*\theta_{M2}-\theta_{M4}$ = 180 or 360^0, the M2 + M4 wave is either lowered or raised respectively; (b) $2*\theta_{M2}-\theta_{M4}$ = 90 or 270^0 produces maximum duration differential between flood and ebb; (c) distortion caused by M6 varies with $3*\theta_{M2}-\theta_{M6} = 0^0$ or 360^0 produces a greater SSE amplitude, whereas 180^0 reduces the amplitude and increases the dwell; (d) $3*\theta_{M2}-\theta_{M6} = 270^0$ produces flood-biased velocity below mean tide level (MTL) and ebb-biased above MTL and for 90^0 the bias is reversed ($A_{M2} = 10*A_{M4} = 10*A_{M6}$); (e) M2+M4+M6 for $2*\theta_{M2}-\theta_{M4} = 90^0$ and $3*\theta_{M2}-\theta_{M6}$ = 0, 360^0; and (f) M2+M4+M6 for $2*\theta_{M2}-\theta_{M4} = 90^0$ and $3*\theta_{M2}-\theta_{M6} = 270^0$ showing distortion of the M2 + M4 wave by M6 at two maximum distortion phases of M6

When unimpeded, the complex interaction of tidal wave, sediment transport and estuarine morphology produces an estuary in equilibrium where the rate of accretion equals the rate of erosion of sediments (zero net sediment flux) (Dyer, 1997) or has a steady bottom profile (Schuttelaars and de Swart, 2000). When subjected to any permanent variation of the forcing parameters, the estuary will find a new equilibrium (Dennis et al., 2000).

For a system not in equilibrium, the morphological evolution depends on the long-term averaged sediment supply (marine or fluvial origin), and the long-term averaged sediment transport (Dronkers, 1986) with the net sediment flux either flood or ebb biased. The fortnightly spring-neap cycle changes the amplitude of M2 (A_{M2}) of the sea-surface-elevation (SSE) and tidal asymmetry may reverse over the cycle (Toublanc et al., 2015). Todeschini et al. (2008) postulated that (for a system without riverine flow) tidal asymmetry diminishes as equilibrium is approached. Dyer (1997), Blanton et al. (2002) and others show that vertical and horizontal tidal asymmetries are due to the shallow water harmonics M4 and M6 (Fig. 2.1); the former generated largely by channel convergence and hypsometry and the latter largely by channel bed friction. M4 causes asymmetry of maximum velocities

(Dronkers, 1986; Dyer, 1997) otherwise known as spatial settling lag (SSL) (De Swart and Zimmerman, 2009; Schuttelaars et al., 2011), whereas Groen (1967) showed that net sediment flux can develop when maximum velocities are symmetrical provided "current variations from maximum ebb to maximum flood current and from maximum flood to maximum ebb current are asymmetrical", when net transport occurs co-directionally with maximum dwell. By contrast, M6 produces zero net flux of fine sediments (Dronkers, 1986).

Rather than M2 and M4, the combination of K1 and K2 is a driver of asymmetry at the mouth of the Murray River in Australia (Jewell et al., 2012) and in the Venice Lagoon (Ferrarin et al., 2015). The latter study focussed on historical changes to tidal range and mean sea level, without specific reference to the constituent interactions which cause asymmetry.

Another asymmetry, temporal settling lag (TSL), the difference between the slack water periods before flood and ebb tides was identified by Dronkers (1986) who deduced that the differences in high water (HW) and low water (LW) slack through a cross-section produce a net sediment flux:

$$S = \mu^{+}\lambda^{+} - \mu^{-}\lambda^{-} \tag{1}$$

where μ^{+} is the amount of sediment accreted during the period of HW slack and λ^{+} is the distance travelled by the tide during the period of HW slack during which the accreted material remains settled (vice versa for μ^{-}, λ^{-} and LW slack). If slack duration at HW is greater than duration of LW slack then net sediment flux is flood biased and vice versa.

Sediment removal is a common practice in estuaries around the globe. Dredging is the most common method although sediment raking on ebb tides and during flooding events is also used and works by mechanically increasing the suspended sediment with a rake towed behind a suitable vessel. Neither method provides a permanent solution as sediment eventually returns to re-establish equilibrium (Dennis et al., 2000). Dredging is becoming increasingly expensive to the point of being cost prohibitive in many cases. Regardless of the method used, the rate of return of sediment must be minimised as much as possible to obtain the greatest efficiency. An understanding of how the altered bathymetry influences the sediment regime is therefore important (Prandle, 2009).

Annual raking of estuarine sediments in the upper Tamar River estuary Tasmania, Australia moves sediment seaward and places the upper estuary into a temporary state *above* equilibrium; i.e. the cross-sectional area of the waterbody is larger than can be supported by the tidal prism; see O'Brien (1966). Raking is conducted during the months of July to September when riverine flow is normally high and over the ensuing months, an estimated 70-90% of the originally displaced sediment returns before the next raking cycle, without fully re-establishing equilibrium. However, sufficient quantities are mobilised to alter the tidal dynamics and this can be monitored with on-going analysis of the local SSE constituents. The bathymetric adjustment is monitored by the Launceston Flood Authority (LFA) on a monthly basis (approximately) providing a volumetric measure of equilibrium imbalance which can be compared with the SSE constituents. Generally, the further the system is from equilibrium, the faster the sediment returns (Davis and Kidd, 2012; Foster and Nittim, 1987; Howard, 1965), which implies that sediment movement asymmetry is co-variant with the degree of equilibrium imbalance.

Stage-velocity diagrams provide visual interpretation of the tidal distortion caused by amplitudes and phases of M4 and M6 over-tides and are preferable to SSE analysis although Friedrichs and Aubrey (1988) maintain that the latter is acceptable (for progressive waves). Moftakhari et al. (2013) used mathematical techniques to create a velocity-time series from the 157-year SSE-time series available to their study. Gräwe et al. (2014) used SSE data from 13 Wadden Sea tide-gauges to study the link between seasonal variations in tidal constituents and coastal residual transport of sediment. The analyses in this paper primarily use SSE data collected over 22 months with velocity data collected over four months providing further insight into the equilibrium imbalance and estuarine dynamics.

This study uses a statistical approach to evaluate the feedback between bathymetric change and tidal dynamics, specifically M2, M4, M6 and M8 SSE constituents, as the upper Tamar River estuary recovers from sediment raking programs in 2014 and 2015. The approach evaluates correlations between tidal dynamics and morphology bearing in mind that the intermediate link, sediment dynamics, involves processes which are often non-linear and will reduce coefficients of determination. Our conclusions are based on a simple model of sediment dynamics which includes suspended sediment concentrations (C) being proportional to u^3 (for sediment transport), Eq. 1 (for settling and erosional lag effects) and the Hjulstrom diagram (for critical velocities and particle sizes) (Hjulstrom, 1939).

The hypothesis of this paper is that both flood and ebb maximum velocities increase as equilibrium is approached and that velocity asymmetry persists and ultimately balances with other asymmetries and lag effects for attainment of equilibrium. Critical parameters are M4 amplitude and phase which develops flood-biased sediment flux, and the combined effect of M4 and M6, which scour the channel and produce longer dwell at high water than low water. Furthermore, at equilibrium M4 and M6 remain influential in terms of SSE and velocity (u), whereas post raking, subtle changes in relative SSE phases of M4 and M6 maintain strong morphological feedbacks. The continuing influences of M4 and M6 at equilibrium move sediments from the channel to the intertidal flats, which favor ebb-biased sediment flux as they build (Dronkers, 1986). It is predicted that without anthropogenic intervention, the intertidal flats ultimately stabilize with accretion balanced by slumping of the banks into the channel and erosion under the action of wind waves. The cycle continues, maintaining both turbidity and zero net sediment flux.

2. Methods

2.1 Site Description

The Tamar River estuary stretches approximately 80 km from the mouth to the tidal extent in the North Esk River (Fig. 2.2). The estuary is mesotidal and hypo-synchronous as tidal heights increase from 2.34 m at the mouth to 3.25 m at the confluence of the Tamar and North Esk Rivers. M4 (0.035 m) and M6 (0.011 m) over-tides are present at the mouth of the Tamar River (Kidd et al., 2014). A silt belt extends ~ 32 km from the head and comprises banks of cohesive silt and a turbid waterbody with a distinct turbidity maximum. The silt belt has accumulated an estimated 15,000,000 m^3 (Foster and Nittim, 1987) of silt over the last ~200 years due to canalisation of the North Esk River, and freshwater flow diversion of the South Esk River to a hydro-electric power station (Davis and Kidd, 2012) at the head of the Tailrace (Fig. 2). Mean river discharge at the Tailrace is 50 m^3s^{-1} with a maximum of 90 m^3s^{-1} when all four turbines are in use (Foster et al., 1986). River discharge through the lower South Esk River (Cataract Gorge) is regulated to 2.5 m^3s^{-1} when river flow is less than the maximum capacity of the power station, but up to 2000 m^3s^{-1} or more during a large flood. The tidal prisms at the mouth of the North Esk River and Yacht Basin/Cataract Gorge (Fig. 2.2) are 1.7 million m^3 and ~325,000 m^3 respectively. Salinity levels are low over the study area and the water body is well mixed (per. obs.), so gravitational circulation (Valle-Levinson, 2010) and internal tides (Jay and Musiak, 1996) are not significant. Detailed site descriptions are available in other publications (BMT_WBM, 2008; Davis and Kidd, 2012; Ellison and Sheehan, 2014; Foster and Nittim, 1987; Kidd et al., 2014; Sheehan and Ellison, 2014). Local features are shown in Fig. 2.2.

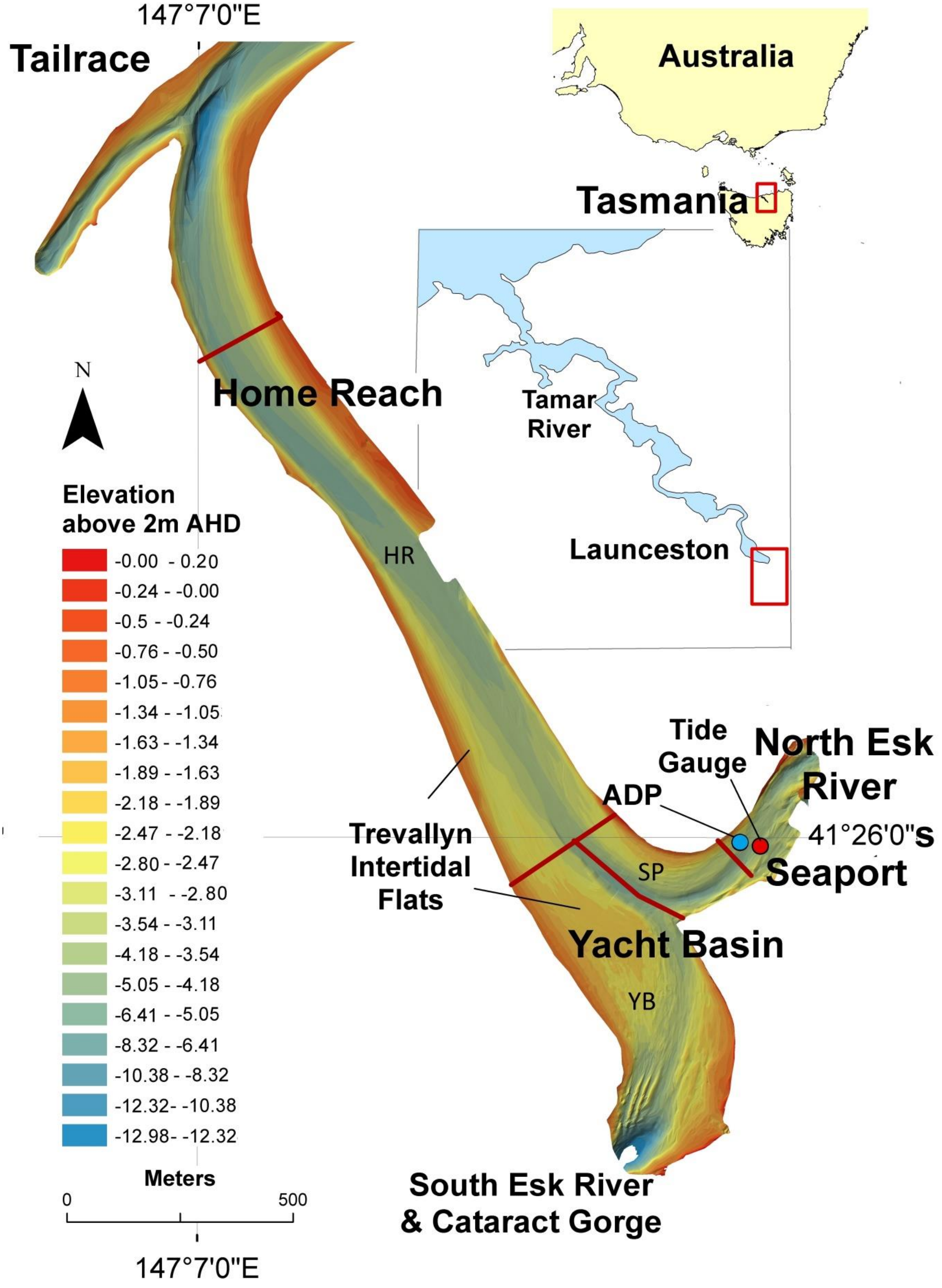

147°7'0"E
Tailrace
Australia
Tasmania
Tamar
River
Launceston
Home Reach
N
Elevation
above 2m AHD
-0.00 - 0.20
-0.24 - -0.00
-0.5 - -0.24
-0.76 - -0.50
-1.05 - -0.76
-1.34 - -1.05
-1.63 - -1.34
-1.89 - -1.63
-2.18 - -1.89
-2.47 - -2.18
-2.80 - -2.47
-3.11 - -2.80
-3.54 - -3.11
-4.18 - -3.54
-5.05 - -4.18
-6.41 - -5.05
-8.32 - -6.41
-10.38 - -8.32
-12.32 - -10.38
-12.98 - -12.32
HR
Tide
Gauge
North Esk
River
ADP
41°26'0"s
Trevallyn
Intertidal
Flats
SP
Seaport
Yacht Basin
YB
Meters
0
500
South Esk River
& Cataract Gorge
147°7'0"E

Fig. 2.2 Location of the upper Tamar River estuary and bathymetric map of the study site following a silt raking program undertaken by the Launceston Flood Authority 2014. Elevations are metres above 2 m Australian Height Datum (AHD) which is approximately the level of mean high water spring tide (MHWS). The site is centred on the city of Launceston, 70 km from the coast. Solid (red) lines show areas (HR, SP and YB) for which silt volumes are calculated. The Tailrace is shown to full extent, the tidal extent of the Cataract Gorge is 400 m beyond that shown and the North Esk River is tidal for 11.7 km. Bathymetric data sourced from Launceston Flood Authority

Coarse sediment in the Launceston reach of the estuary is present mostly as flocculated clay rather than sand. A distinct sand belt exists near the tidal extent of the North Esk River although it is only visible after flooding (pers. obs.).

The annual silt raking program is undertaken to improve the physical and visual amenity of the upper estuary, by deepening of the Yacht Basin and Seaport, and removal of the intertidal mud flat adjacent to the Trevallyn foreshore (Fig. 2.2). This natural feature, which has existed from at least the time of European settlement (Welsh, 1830), is removed to allow rowing regattas and dinghy sailing which are recognised as important ecosystem services provided by the estuary (Davis and Kidd, 2012).

The wind velocity pattern for the study site is mostly light with the occasional windy day in the winter months, windier conditions around the spring equinox and fresh sea-breezes during summer months.

2.2 Field Measurements

A tide gauge, comprising a stilling well and two OneTemp™ data loggers (top and bottom), was deployed from July 2014 to May 2016 on a pylon in the North Esk River close to the confluence with the Tamar River (Fig. 2.2). The loggers recorded hourly air pressure, water pressure and water temperature. The variables were analysed using OnSet software (HoboWare Pro) to give a water depth corrected for variations in water density and atmospheric pressure. The data were processed in MATLAB using the *t_tide* plug-in (Pawlowicz et al., 2002). SSE data were analysed on a monthly basis over two monthly windows giving 21 samples over 22 months. The output contained the tidal constituent amplitudes (and error), phase angles (and errors) and signal-to-noise ratios. The sea-surface-elevation (SSE) wave forms were reconstructed from M2+M4+M6+M8 using the equation $y = \sum A_{Mi} cos(\omega_{Mi} t - \theta_{Mi})$, where y is the sea height, A_{Mi} is constituent amplitude, ω_{Mi} is angular velocity, t is time, θ_{Mi} is phase angle and i = 2, 4, 6 and 8 (Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988), and compared with monthly changes to silt volumes (ΔV).

An ADP was deployed from 4th January 2016 to 4th May 2016, adjacent to the tide gauge. Velocity data were collected for bin heights (above the bed) 0.9 m to 1.4 m, and 1.4 m to 1.9 m with a sampling frequency of one hour The data were used to plot velocity-stage diagrams for each bin level. The velocity of the tidal constituents M2. M4, M6 and M8 (u_{M2}, u_{M4}, u_{M6} and u_{M8} respectively), were obtained using *t_tide* for neap and spring tides (January March and April 2016) and for the two monthly period March to April 2016.

The Launceston Flood Authority (LFA) conducts regular bathymetric surveys of the upper estuary using a single beam sonar logger equipped with a GPS to record depths over a series of traverses. A manufacturers accuracy rating of ± 0.03 m is typical for such instruments http://www.syqwestinc.com/media/support/depthmeasuringtechniques.pdf (accessed 3/3/2017). The data were input to ArcGIS (ESRI, USA) to produce a bathymetric chart (Fig. 2.2) and to calculate the monthly volumetric change. The volume of sediment above a datum of -15 m AHD was used as a measure of the system’s closeness to equilibrium. Using XLSTAT (Addinsoft, USA) plug-in for Microsoft Excel, multivariate relationships and Pearson correlation coefficients were determined using a principal component analysis (PCA) for the pairwise correlations between ΔV, M2, M4, M6 SSE amplitudes, and relative phase angles. A measure of the combined influence of M4 and M6 is the vector sum relative to M2 ($(\overline{\mathrm{M4}} + \overline{\mathrm{M6}})/\mathrm{M2}$) (Fig. 3d) and was calculated using the formula,

$$A_{M4}/A_{M2}*(\sin(\theta_{M2}-\theta_{M4}/2))+A_{M6}/A_{M2}*\sin(\theta_{M2}-\theta_{M6}/3). \tag{2}$$

This parameter has important implications for the development of high and low water lags (Fig. 2.1f). At high water the terms in Eq. 2 combine to increase the lag of either of the terms, whereas at low water the combination reduces the dwell of either of the terms.

Errors involving multiple variables were calculated using,

$$\xi_{f(x,y)} = \sqrt{\left(\xi_x \frac{\delta f}{\delta x}\right)^2 + \left(\xi_y \frac{\delta f}{\delta y}\right)^2}, \tag{3}$$

where ξ denotes error in *f, x or y*.

3. Results

3.1 Silt volumes

Silt volumes were calculated for three different areas by the LFA; Yacht Basin and Seaport (YB+SP), Yacht Basin (YB) only, and Home Reach (HR) (Fig. 2.2). Silt volumes for the combined areas of HR and SP are shown with the river flows and raking periods (Fig. 2.3a). The volume reduction in June 2015 was due to sediment transfer from Home Reach into the Yacht Basin as a flood-biased sediment flux dominated the upper estuary. Raking was less effective in 2015 than 2014 due to a lack of high flow events.

The volume for Home Reach and Seaport (HR+SP) represents the volume of silt above -15m AHD in the main estuary immediately downstream of the tidal gauge. The periodic surveys were used to calculate the monthly change in HR+SP silt volume (ΔV) (Fig

2.3d). Raking re-distributed some silt into the channel which was raised ~ 3.4 m in places (not shown). The raking process requires high river flows (Fig 2.1a) and the 2015 campaign moved only ~40,000 m^3 of silt, whereas a large flood in July 2016 removed >300,000 m^3 with minimal raking (not shown).

3.2 Constituent analysis

The SSE amplitude of M2 (A_{M2}) was used to calculate a ratio to harmonics M4 and M6 (Fig. 2.3b). A_{M2} varies from 1.37 m to 1.48 m and shows some covariance with ΔV and $(\overline{M4}+\overline{M6})/M2$ (Fig.2.3d). A correlation between ΔV and $(\overline{M4}+\overline{M6})/M2$ was found (R^2 = 0.44, $p < 0.001$) using regression (not shown).

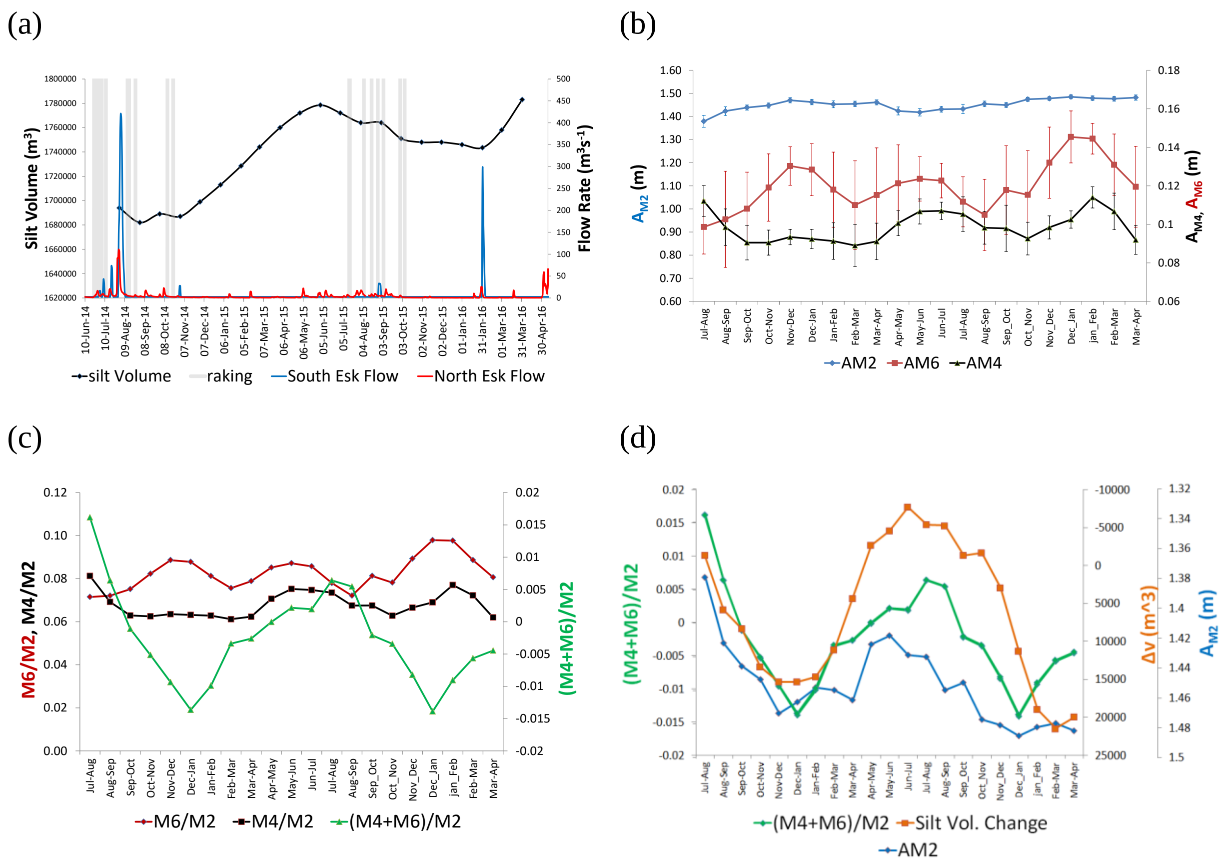


Fig. 2.3 SSE constituent amplitudes, relative phase angles, total and monthly changes in silt volumes (V and ΔV respectively) (a) Silt volumes for Home Reach plus Seaport,

periods over which raking was conducted and river flows over the study period, (b) monthly M2, M4 and M6 SSE amplitudes show some seasonal variation, (c) A_{M4} and A_{M6} relative to A_{M2} are cyclic, but generally A_{M6} is greater and combine in their vector sum $((\overline{M4} + \overline{M6})/M2)$ synergistically (> 0) and antagonistically (< 0), (d) three month running mean of monthly change in silt volume (ΔV), A_{M2} and $(\overline{M4} + \overline{M6})/M2$ show similar trends (note inverted axes)

The upper estuary returns towards a maximum silt volume following scour by raking or flood (Fig. 2.3a). The dataset starts in 2008 (not shown) and similar asymptotic returns to equilibrium are evident following previous periods of dredging and flood scour.

3.3 Principle Component Analysis

Four factors were generated using XLSTAT, with the first two explaining 76.3% of the variance (Fig. 2.4a); the second and third 33.6% (Fig. 2.4b); third and fourth 17.2% (not shown). The correlations between variables are shown in Table 2.1.

(a) (b)

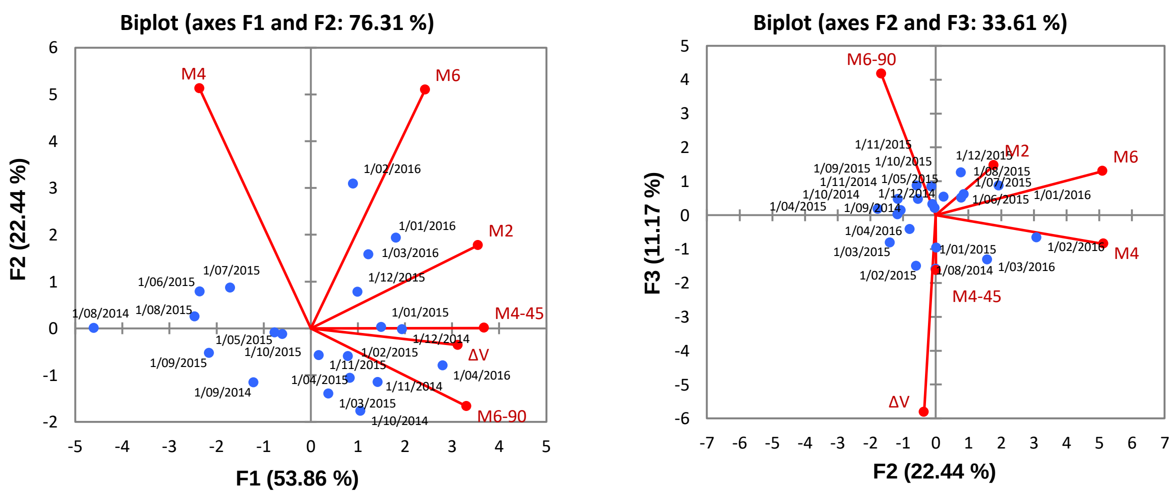


Fig. 2.4 The bi-plot results of the PCA; "M6-90" represents the difference between the relative phase of M6 and 90 degrees and is a measure of the effectiveness of θ_{M2}-θ_{M6}/3 to create dwell at high water. Similarly "M4-45" is a measure of the effectiveness of θ_{M2}-

$\theta_{M4}/2$ to produce flood-tide velocity bias. Data points <d/mm/yyyy> are mid-points of sample periods

Data point groupings (Fig. 2.4a) generally show winter to the left (raking periods) and summer to the right of F1 = 0. The top/bottom divide around F2 = 0 is not clear but could be related to seasonally higher tides around the equinoxes in March and September.

Table 2.1 Correlation matrix (Pearson (r)) of amplitudes and relative phases derived by PCA. Values in bold type are statistically significant ($p < 0.05$)

Variables	ΔV	M2	M4	M6	M4-45	M6-90
ΔV	**1**	**0.488**	-0.383	0.309	**0.644**	0.366
M2	**0.488**	**1**	-0.325	**0.656**	**0.618**	**0.536**
M4	-0.383	-0.325	**1**	0.242	-0.421	**-0.593**
M6	0.309	**0.656**	0.242	**1**	**0.444**	0.321
M4-45	**0.644**	**0.618**	-0.421	**0.444**	**1**	**0.585**
M6-90	0.366	**0.536**	**-0.593**	0.321	**0.585**	**1**

An equally weighted comparison of SSE phases θ_{M4} and θ_{M6} relative to θ_{M2} is given by $\theta_{M2} - \theta_{M6}/3$ and $\theta_{M2} - \theta_{M4}/2$. A plot of the relative phases suggests a narrow band of possible values at regime (Fig. 2.5a). The trend line of Fig. 2.5a can be approximated to $y = 0.3 * x + 90$. Applying cosine gives $\cos(y) = -\sin(0.3*x)$ or

$$\cos(\theta_{M2}-\theta_{M6}/3) + \sin(0.3*(\theta_{M2}-\theta_{M4}/2)) = 0 \qquad (4)$$

The plot of Eq. 4 (not shown) has a non-zero y intercept and non-unity slope and the best result (slope =1.026, y intercept = -0.019, $R^2 = 0.341$, $p < 0.05$) is obtained from

$$\cos(\theta_{M2}-\theta_{M6}/3) + \sin(0.25*(\theta_{M2}-\theta_{M4}/2)) = 0 \qquad (5)$$

(a) (b)

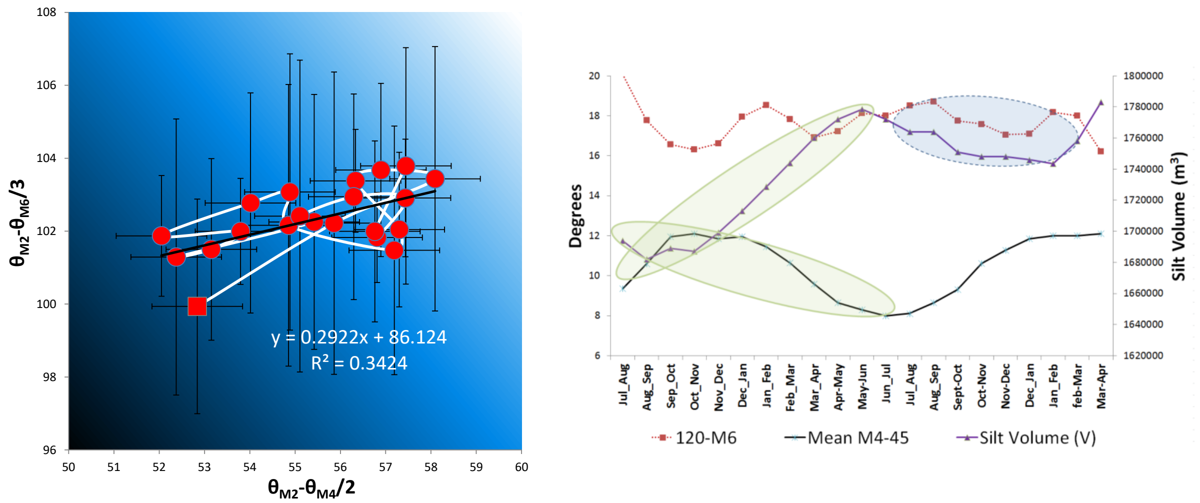


Fig. 2.5 Analysis of SSE constituent phases and total silt volume (V). (a) The transition of relative phases from July 2014 (bottom left) showing distinct grouping within a specific band. The darker shading represents greater influence of M4 (maximum at θ_{M2}-$\theta_{M4}/2$ = 45^0) and the influence of M6 is discussed in the text (different effects at θ_{M2}-$\theta_{M6}/3$ = 90^0 and 120^0). The likely values at equilibrium are (58 ± 2^0, 103.5 ± 1^0) when both phases are ~13^0 from maximum flood dominance (M4) and maximum dwell (M6+M4). Errors are large (particularly θ_{M6}) as phases were calculated over periods of two months, and (b) a comparison of three monthly mean of M4-45, and 120-M6 with total silt volume, showing changing correlations as silt volumes reduce

The divergence of θ_{M2}-$\theta_{M4}/2$ from 45^o represents lessening of flood dominance due to M4 harmonic, whereas the divergence of θ_{M2}-$\theta_{M6}/3$ from 90^0 lessens the dwell at high water caused by the combined effects of M4 and M6 (Fig. 2.1f) and divergence from 120^0 increases the dwell at high water (see Fig. 2.1e and 2.1f). θ_{M2}-$\theta_{M6}/3$ is 12±2^0 from 90^0 which implies longer dwell at high water than at low water. Seasonal fluctuations cannot be excluded as the cause of the rather periodic M6-90 and M4-45 variations (Fig 2.5b). When volumes are decreasing, M4-45 generally increases and when volumes are increasing, M4-45 generally decreases (Fig. 2.5b). The smaller the value of M4-45 the greater is the influence of θ_{M2}-$\theta_{M4}/2$, the implication being that raking induces a change in $\theta_{M2} - \theta_{M4}/2$ closer to 45^{o} and a greater influence of SSL/velocity asymmetry. When V is low but increasing (Fig. 2.5b), the correlation between V and M4-45 is high ($R^2 = 0.86$, $p < 0.001$), whereas when sediment volumes are high but decreasing (Jul-Aug 2015 to Jan-Feb 2016), M4 becomes less influential and V and 120-M6 become correlated ($R^2 = 0.53$, $p < 0.05$), which is not the case over the whole study period (R^2= 0.001).

3.4 Velocity and SSE time series

Velocity and SSE time series are useful tools in the evaluation of spatial and temporal settling lags. The plots (Fig. 2.6) confirm that flood duration remains shorter than ebb duration and the slope lines on the plot at zero velocity are indicative of differing rates of change in velocity around slack water and temporal settling lag (Dronkers, 1986).

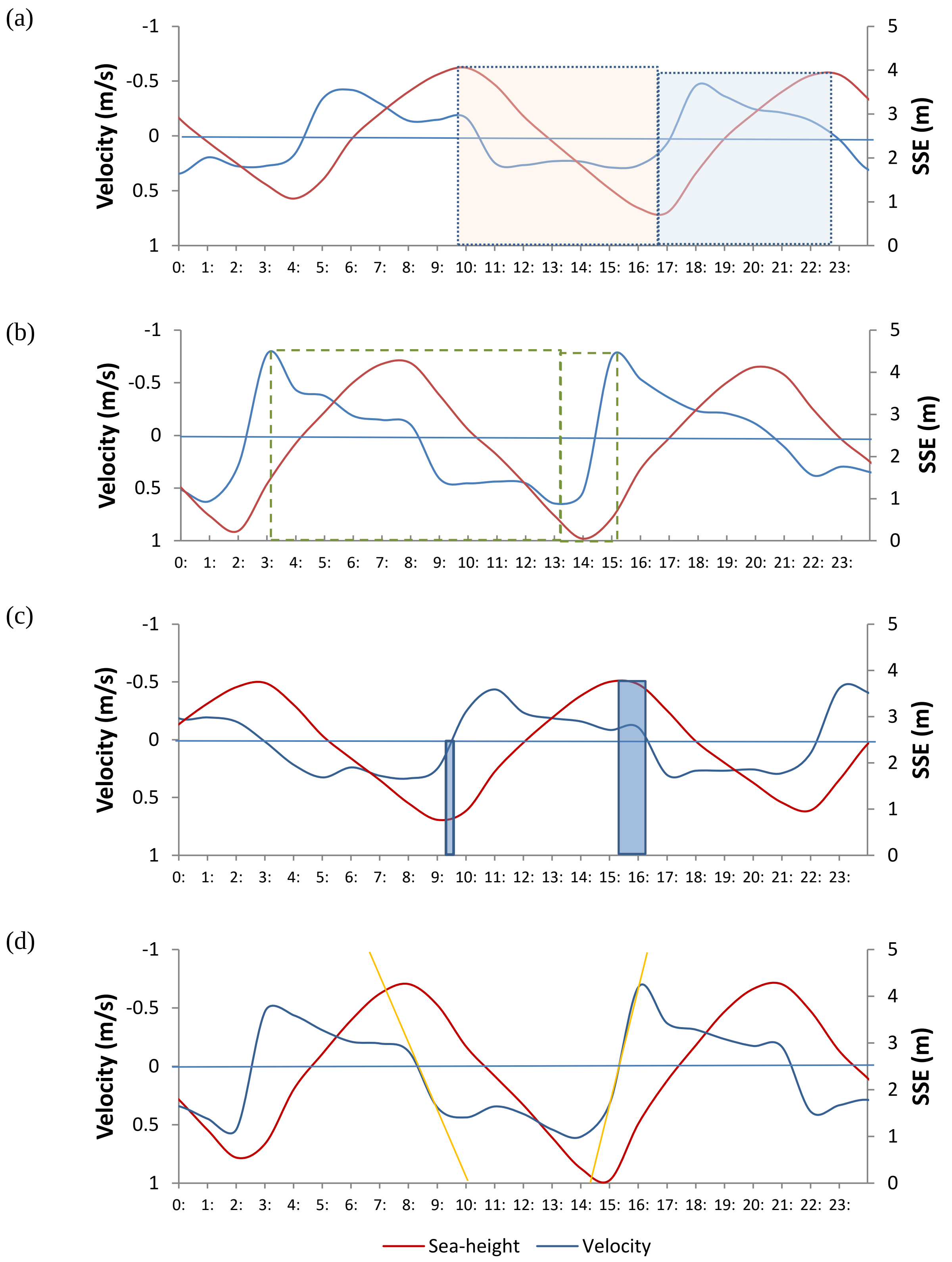


Fig. 2.6 Near bed SSE and velocity time series and asymmetries for neap and spring tides over 4 separate days for bin level 0.9 m to 1.4 m, (a) neap tide of 5th March 2016,

with shaded areas showing velocity asymmetry (SSL); (b) spring tide of 15th March 2016, with shaded areas showing duration asymmetry between maximum velocities (SSL) (c) neap tide of 23rd March 2016 with shaded areas showing lag between high water - high water slack and low water - low water slack (TSL) and (d) Spring tide of 14th March 2016 with lines showing |du/dt| at SBF and SBE (TSL)

Duration of flood (Fig. 2.6a) is consistently less than duration of ebb (width of dotted rectangles) indicating an on-going influence of M4. The time differential between maximum velocities (dotted periods in Fig. 2.6b) is the asymmetry described by Groen (1967). The parameter |du/dt| is used to identify temporal settling lag (Dronkers, 1986) at zero velocity (solid straight lines Fig. 2.6d). The neap tides (Fig. 2.6a and 2.6c) show similar |du/dt| values at SBF and SBE, whereas the spring tides show longer dwell at high water (SBE) and therefore flood biased sediment flux. Both neap and spring tides show lag between high water - high water slack and low water - low water slack (Fig 2.6c). The longer lag described by Groen (1967) is consistent with a lesser |du/dt| described by Dronkers (1986) and vice versa.

3.5 Velocity-stage plots

Velocity-stage data were collected from 4th January 2016 to 4th May 2016 (Fig. 2.7)

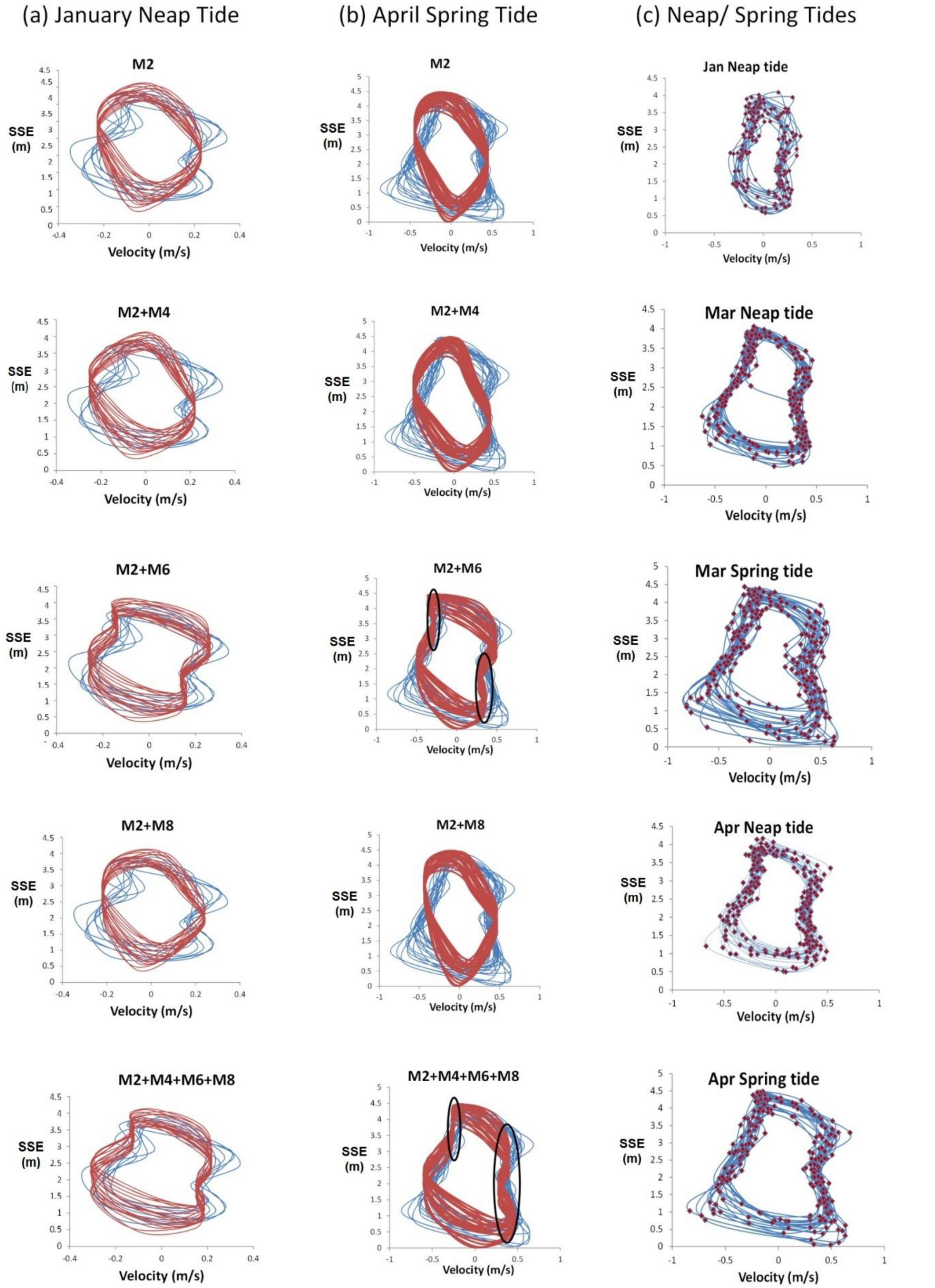


Fig. 2.7 Blue lines represent sampled data; red lines are reconstructed velocity against sampled SSE. (a) Near bed (bin 1.4 m to 1.9 m) constituent velocity-stages superimposed

on tidal velocity-stage plots for the period 4th to 14th January 2016; (b) the spring tide from 8th to 18th April 2016 and (c) Neap and spring tides for March and April 2016 showing sampling time distribution (red diamonds). Maximum neap tides are almost symmetrical whereas spring tides show flood velocity bias

The stage-velocity plots show distortion (Fig. 2.7) due to the combined effects of M4, M6 and M8, although M8 has little influence on SSE. Clearly u_{M6} has a major influence, producing a near constant velocity before ebb and flood (see highlighted area Fig. 2.7b, rows 3 and 5) and being either synergistic (adding) or antagonistic (reducing) with M4 at other parts of the cycle (Fig. 2.7c, Fig 2.3c).

Maximum neap tidal velocities were symmetrical for each sampling period but increased from 0.33 m/s in January to 0.5 m/s in April. Spring tides were asymmetric; -0.8 to +0.6 $m.s^{-1}$ in March, increasing to -0.83 and +0.63 $m.s^{-1}$ in April. Spring tide data for January were not recorded. The M6 velocity was particularly significant with the ratio u_{M6}/u_{M2} varying from 0.35 for neap tides to 0.39 for spring tides (Table 2.2). Constituent velocities for the period 3rd March 2016 to 30th April 2016 are shown at Table 2.2.

Table 2.2 Constituent velocities derived by t_tide for the neap tides from 4th January to 14th January 2016 and spring tides from 8th April to 18th April 2016, showing consistently high u_{M6} amplitudes, a doubling of u_{M2} and u_{M6}, and an almost quadrupling of u_{M4}. Also a comparison of SSE and velocities for March - April 2016, boxed data shows the phase lag between u_{M2} and A_{M2} is 47.25 ± 0.73^0

Tide	Frequency (hr^{-1})	Amplitude u; SSE ($m.s^{-1}$; m)	Amplitude Error ($m.s^{-1}$; m)	Phase (degrees)	Phase Error (degrees)	Signal to noise ratio (SNR)	Relative Phase (deg.)	R. Phase Error (deg.)
January neap tide (u)								
M2	0.0805114	0.2104	0.031	248.61	7.6	47	0	7.6
M6	0.2415342	0.0728	0.03	240.83	24.9	6	145	26.0
M4	0.1610228	0.0266	0.014	253.75	25.8	3.8	63.5	26.9
April spring tide (u)								
M2	0.0805114	0.4244	0.079	347.6	10.2	29	0	10.2
M6	0.2415342	0.1667	0.068	170.19	22.1	6.1	152.6	37.6
M4	0.1610228	0.0988	0.024	79.51	12.3	16	75.7	23.7
March-April velocities (u)								
M2	0.0805114	0.382	0.009	$\boxed{193.19}$	1.1	2.00E+03	0	15.8
M6	0.2415342	0.111	0.051	74.17	24.1	4.8	325.1	24.4
M4	0.1610228	0.0795	0.014	133.95	10.5	31	72.4	10.7
March-April (SSE)								
M2	0.0805114	1.482	0.023	$\boxed{241.16}$	0.9	4.30E+03	0	0.9
M6	0.2415342	0.1195	0.042	52.11	19.3	8.3	311.4	19.5
M4	0.1610228	0.0919	0.015	7.43	10.6	37	114.9	10.7

For a progressive wave, A_{M2} lags u_{M2} by 90^0 or 283^0 for θu_{M2} = 193^0 (Fig. 2.8). A_{M2} and u_{M2} phases for March-April have a lag of 42^0 placing SSE_{M2} ~1.45 hours earlier than expected. The angle of greatest influence (AGI) for θu_{M2} - $\theta u_{M4}/2$ is ~ 75 ± 5^0; AGI for θ_{M2} - $\theta_{M6}/3$ is 120 ± 9.3^0.

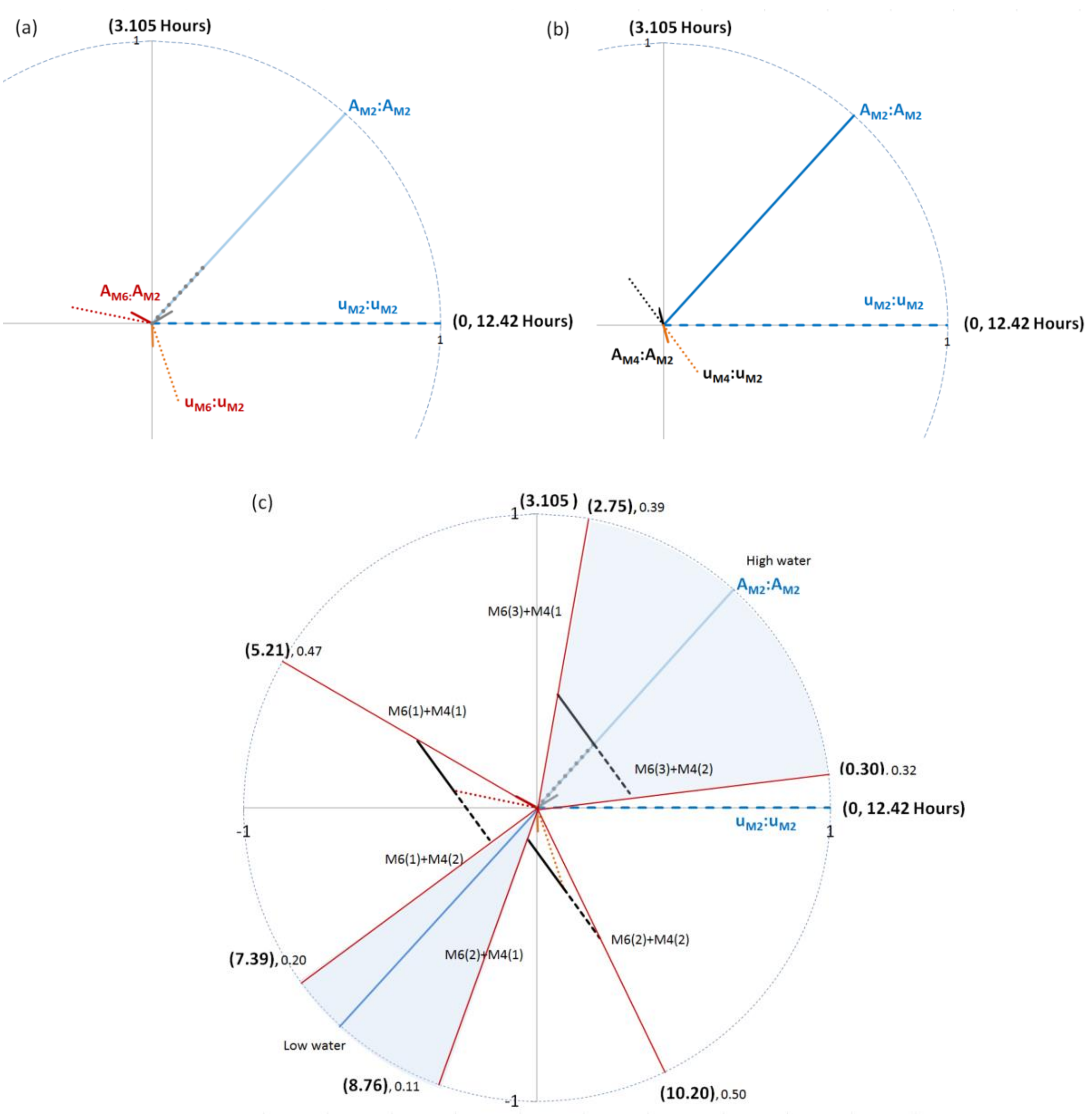


Fig. 2.8 Vectors showing timing (radial lines), relative phases and relative amplitudes of M2, M4, M6 and $\overline{\mathbf{M4}}+\overline{\mathbf{M6}}$ for the two month period March and April 2016. For every cycle of M2, M4 completes two cycles, M6 completes 3 cycles and $\overline{\mathbf{M4}}+\overline{\mathbf{M6}}$ completes six cycles; M4(1) + M6(2) refers to the vector sum of velocities for the first cycle of M4 and the second cycle of M6 etc.; (a) the third cycle of u_{M6} coincides with A_{M2}; (b) M4 is close to a standing wave; (c) $\overline{\mathbf{M4}}+\overline{\mathbf{M6}}$ maxima are >2 hours apart

at high water and <1 hour apart at low water (shaded areas) with minima at high and low water. Number in brackets is time after maximum u_{M2} followed by $\overline{\mathbf{M4}} + \overline{\mathbf{M6}}$ amplitude (smaller font)

$\overline{\mathrm{M4}} + \overline{\mathrm{M6}}$ maximises before MTL on the flood tide (M4(2) + M6(2)) with the next greatest maxima before MTL on the ebb tide (M4(1) + M6(1)). Two minima coincide with high and low water. The phase lag between u_{M6} and A_{M6} is close to 90^0. M6 is therefore a progressive wave and for θ_{M2}-$\theta_{M6}/3 = 102.5\pm1^0$, is 12.5 ± 1^0 from the angle of greatest peak/trough advance (Fig. 2.1f). At low water u_{M4} and u_{M6} are antagonistic, producing a minimum with maxima approximately half an hour both sides and a short dwell. At high water the velocities are again antagonistic; $u_{(\overline{M4} + \overline{M6})}$ is at one of its minima and a longer dwell exists between respective maxima (Fig. 2.8c). With $A_{M6} > A_{M4}$ and u_{M6} almost $2*u_{M4}$, M6 is a major influence on sediment dynamics.

4. Discussion

4.1 Increasing velocities and turbidity

Other than two brief high flow events, river flows remained mostly constant over the study period and are assumed to have had little effect on results. The tidal prism in the North Esk River upstream of the raked areas also remained constant throughout the study. As equilibrium approached, the velocity in the raked areas increased due to the contracting channel cross-sectional area. Spring tides show a greater asymmetry than neap tides and the velocities of both increased as equilibrium was approached. The maximum spring tide ebb velocity was 0.63 m/s at mid tide and again at low water (Fig. 7) which far exceeds the critical erosion velocity for silt larger than 0.01 mm (Hjulstrom, 1939). As the sediment carrying capacity (C) is proportional to u^3 then the capacity increased eight fold from the neap tide in January to the spring tide of April. Sediment flux therefore increases as equilibrium is approached which is consistent with the conclusion of Prandle (2009) that maximum concentrations coexist with conditions of morphological stability. Dronkers (1986) concluded that channel friction (and hence M6) has no influence on net sediment flux, which although generally accepted, cannot be confirmed by this study. However, $u_{M6} > u_{M4}$, and as ebb velocity below mean tide level (MTL) is due largely to M6 (Fig 2.7c row 3) and ebb-directed sediment is returned on the flood, it can be concluded that in the upper Tamar, M6 plays an important role in maintaining high turbidity throughout the tidal cycle.

4.2 Flood bias and θ_{M4}

The relevant SSE correlations over the study period are θ_{M4} with ΔV ($r = 0.488$, $p < 0.05$) and A_{M2} ($r = 0.618$, $p < 0.05$) and more particularly, for the period of increasing V from July 2014 to July 2015 (Fig. 2.5b), V and M4-45 were highly correlated ($R^2 = 0.86$, $p < 0.001$).

The system approaches SSE θ_{M2}-$\theta_{M4}/2 = 58\pm3^0$ which is 13 ± 3^0 from the maximum flood dominance of 45^0 for a progressive wave (Friedrichs and Aubrey, 1988). M4-45 reacted to raking by moving to a more active phase angle (see Fig. 2.5b) and increasing flood-velocity bias. However u_{M4} is close to a standing wave (Fig. 2.8) and maximum M4 velocities are skewed closer to low water on the ebb and high water on the flood. Nevertheless, velocity asymmetry is maintained (~0.6 to ~0.5 ms^{-1}) and the maximum carrying capacity of the flood is ~70% greater than the maximum capacity of the ebb. It is concluded that a causal effect exists between θ_{M2}-$\theta_{M4}/2$ and flood-biased sediment flux in the upper Tamar.

4.3 Dwell at high water and $\overline{M4} + \overline{M6}$

Dyer (1997) states that the superposition of M2 and M4 in terms of height and velocity represents the major part of tidal asymmetry and the ratio of elevation amplitudes

(A_{M4}/A_{M2}) governs the dominance of the SSL asymmetry, either ebb or flood (Speer and Aubrey, 1985). However, results show that M6 plays an important role in the tidal dynamics of the upper Tamar River estuary.

Results show a correlation of ΔV with $(\overline{\mathrm{M4}} + \overline{\mathrm{M6}})/\mathrm{M2}$, which does not imply causation or that any causation applies in reverse. According to Friedrichs and Madsen (1992) net sediment flux is more sensitive to changes in channel depth than intertidal storages by a factor of 5/3. The important parameters are *a/h* and V_i/V_c where *a* is tidal amplitude, *h* is mean water depth, V_i is volume of intertidal storage and V_c is channel volume. V_i/V_c can be parameterised as $\Delta b/b_c$, where Δb is the change in channel width (b_c) between low and high water. The function $\gamma = 5a/3h - \Delta b/b_c$ is ≥ 0 for flood dominance and ≤ 0 for ebb dominance (Blanton et al., 2002). In the upper Tamar, Δb reduced and b_c increased as a result of raking, hence γ >> 0 and the system was flood dominant. However, as the system approaches equilibrium, the channel scours, *h* increases and *5a/3h* decreases, so that for a sufficiently large *h* the system tends towards possible ebb dominance. Similarly $\Delta b/b_c$ (or V_i/V_c) increases as the tidal banks reform further reducing γ. This explains how u_{M6} and $\overline{\mathrm{M4}} + \overline{\mathrm{M6}}$ counter the flood-biased sediment flux caused by M4. The SSE phase $\theta_{M2}-\theta_{M6}/3$ determines the timing of the strong ebb currents before low tide which deepen the channel and $\overline{\mathrm{M4}} + \overline{\mathrm{M6}}$ determines the dwell at high water; hence the delay in returning to the ebb and the strengthening of the ebb currents. A causal link between M6 (more precisely $\overline{\mathrm{M4}} + \overline{\mathrm{M6}}$) and ebb-sediment flux is established and the system approaches equilibrium despite M4 remaining close to maximum flood-biased phase.

4.4 Channel scour

Another process occurring during the return to equilibrium, and confirmed by bathymetric survey, is the deepening of the channel caused by the high velocities pre and post low water. The velocity-stage plots (Fig 2.7 row 3) indicate that u_{M6} has a major influence particularly during the ebb. Pethick (1994) showed how this process marked the transformation of a flood dominant estuary into ebb dominance and according to Heathershaw and Hammond (1980) this "near bottom flow component" is directed up slope during both ebb and flood.

Velocities almost doubled (Table 2.2) and asymmetry increased (Fig. 2.7c) as equilibrium approached and were sufficiently strong (> 0.6 $m.s^{-1}$) before and post low tide to scour sediment from the channel under the influence of M6 (Fig. 2.7 row 3, Fig. 2.8c). Fine silt particles (~ 0.01 mm) begin to settle at low water slack ($u < 0.001$ $m.s^{-1}$), and quickly resuspend under the influence of flood velocities over 0.1 $m.s^{-1}$ and transport in suspension until $u < 0.01$ $m.s^{-1}$ at high water (Hjulstrom, 1939; Soulsby et al., 2013). Therefore, channel scour occurs on both ebb and flood and especially during spring tides. Higher banks remain inundated for ~ 2 hours at high water, allowing some silt to settle and remain as the SSE drops approximately one metre before ebb velocity is sufficient to resuspend fine/coarse silt from lower elevations.

4.5 The feedback loop

The above discussion indicates a feedback loop existed between tidal dynamics, sediment dynamics, net sediment flux and bathymetry. At equilibrium net sediment flux is zero, although turbidity remains high and sediment movement still occurs. In this situation, Prandle (2009) argues that the sediment regime is a consequence of the bathymetry (see 4.9). Arguably, the feedback loop will be static with bathymetry directly affecting the sediment regime through constant tidal constituents, but the loop will always exist in the presence of variable forcing factors creating a state of dynamic equilibrium.

4.6 Dynamic Equilibrium

External forces such as anthropogenic influences, river flow and sea-level rise rarely remain constant. The mean monthly sea-level at the mouth of the Tamar River rose > 1 mmyr^{-1} from 2002 to 2012 (www.bom.gov.au, accessed July 2016) and South Esk River flows through the Cataract Gorge changed from unrestricted to 1.5 m^{3}s^{-1} and then 2.5 m^{3}s^{-1} over the last 60 years. Results show variations of constituent amplitudes and phases between neap and spring tides plus natural variations over seasonal, annual and longer periods. Stability therefore is best described in terms of dynamic equilibrium (Fig. 2.9) as silt volumes will naturally change along a continuum dependent on the variation of forcing factors mentioned above.

4.7 Dwell effects and tidal flats

Fig. 1f, Fig. 2.7 (row 6) and Fig 2.8c show how M4 and M6 combine antagonistically to produce a longer dwell at high water than at low water which delays the return to ebb and increases ebb velocities (Friedrichs and Aubrey, 1988). This effect may be the reason why the ratio $(\overline{\mathrm{M4}} + \overline{\mathrm{M6}})$/M2 has a correlation with ΔV whereas M4/M2 and M6/M2 do not (Fig. 2.4c and 2.4d).

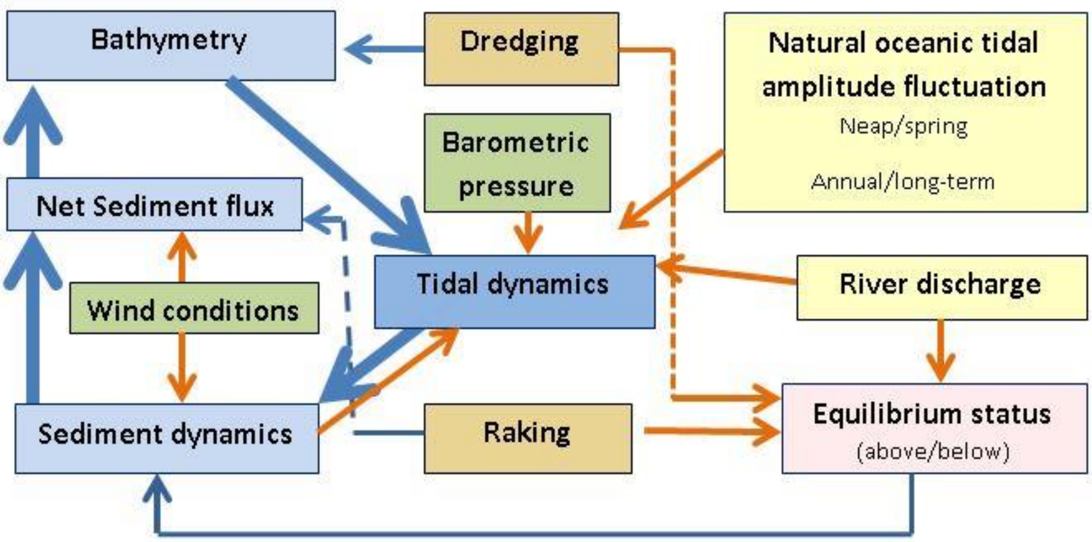


Fig. 2.9 The influences on tidal dynamics and the feedback loop with sediment dynamics, sediment flux and bathymetry (bold blue arrows). The natural forcing

produces a dynamic equilibrium in a system without anthropogenic forcing (raking, dredging). The immediate impact of dredging is on the bathymetry, whereas the immediate impact of raking is on the net sediment flux. Both influence the equilibrium status of the system, as does river discharge. Wind directly influences sediment flux particularly over intertidal flats and barometric pressure has an inverse relationship with SSE amplitude

Dronkers (1986) described TSL asymmetry as a difference between the periods of slack water before ebb and flood tides ($|du/dt|_{SBE} \neq |du/dt|_{SBF}$), where u is tidal velocity, t is time, SBE denotes slack before ebb, and SBF denotes slack before flood (Fig. 2.6). $\overline{M4} + \overline{M6}$ is antagonistic at high water (lowering |du/dt|) but less so at low water (Fig. 2.1f, Fig 2.8c) and therefore drives TSL asymmetry. TSL asymmetry particularly affects the residual transport of fine sediment in the suspended load, whereas SSL affects transport of coarse particles in the bed load (Dronkers, 1986). The upper Tamar River estuary around Launceston is noted for a lack of coarse/sand-sized particles (Foster and Nittim, 1987) with the sand belt being further upstream within the North Esk River (pers. obs.). The annual raking program removes natural intertidal banks from the Trevallyn foreshore and the Seaport Marina (Fig. 2.2) which decrease high water dwell and must increase the flood-biased sediment flux.

4.8 Re-suspension by wind waves

Wind waves are a forcing factor which influence sediment dynamics (Dronkers, 1986; Fagherazzi et al., 2007). Wave energy which dissipates over shallower (unvegetated) areas has a greater effect at high water than low water and produces a net export of fine sediment

(Dronkers, 1986) (hence the importance and relative stability of intertidal flats), especially in estuaries with tidal flats above mean sea level.

4.9 Sediment regime

Prandle (2009) found that sediment loads (regimes) are a consequence of estuarine bathymetry, which is contrary to the commonly held paradigm that sediment regimes determine the bathymetry. Considering the main feedback loop of Fig. 2.9, the net sediment flux at equilibrium is zero although turbidity will remain high, and the feedback from net sediment flux to bathymetry is lost. At equilibrium the link between bathymetry, tidal constituents (especially M4 and M6) and sediment regime remains, vindicating Prandle's argument.

The fine suspended sediments (< 0.01 mm in size) in the upper Tamar do not settle easily, even in a centrifuge (N. Bose, pers. comm.), and remain in suspension over the tidal cycle. Fine sediment is transported downstream where flocculation occurs when mixed with salt (Foster et al., 1986). Coarse, flocculated sediment is transported upstream under the influence of M4, where some will settle at SBE on the intertidal banks.

4.10 The raking process

During the raking process, V decreased (as intended), M4 became less influential and V and 120-M6 became correlated ($R^2 = 0.53$, $p < 0.05$). Note also the 120-M6 vector, although not shown, would be diametrically opposite M6-90 on the PCA bi-plot (Fig. 2.4a) placing it close to the sampling dates corresponding to raking periods. It is generally understood that $3\theta_{M2}-\theta_{M6}$ does not produce net sediment flux (Dronkers, 1986) and therefore cannot have a causation effect on V. Therefore, although unproven by this study, it is likely the causation is the reverse and raking produces a direct response in M6.

9. Conclusion

This study found that sediment flux asymmetry is a delicate balance between competing influences; velocity asymmetry caused by M4, a partly competing dwell asymmetry caused by the combination of M4 and M6, a general increase of velocity as regime is approached, the natural variance of the forcing oceanic tide, lag effects and varying river discharge. At different stages of the tidal cycle M4 and M6 are antagonistic and synergistic with the ratio of the vector sum to A_{M2} $((\overline{M4} + \overline{M6})/M2)$ having a higher correlation with silt volume change (ΔV) than the individual ratios A_{M4}/A_{M2} and A_{M6}/A_{M2}, possibly due to the longer dwell created at high water by $(\overline{M4} + \overline{M6})$. A relationship ($R^2$ = 0.34, $p < 0.05$) between the relative SSE phases of M4 and M6 was found; $\cos(y) = -\sin(0.25*x)$, where y is relative phase of M6 and x is the relative phase of M4. Paradoxically, as regime is approached, M4 phase remained close to maximum flood dominance and the study confirmed that tidal velocities increased and the channel deepened as the system recovered from raking. Results indicate a feedback loop between relative SSE phases of M2, M4 and M6, sediment dynamics, net sediment flux and bathymetry. Although PCA correlations were statistically significant ($p < 0.05$), coefficients of determination were generally less than 65% between variables possibly due the non-linearity of sediment dynamics. Nevertheless it was shown that M6 phase and velocity produced strong ebb currents before low tide which deepened the channel and produces an ebb sediment flux which partly countered the flood sediment flux caused by M4. SSE phases were influenced by natural variability in oceanic sea-surface-elevation, in particular the amplitude of M2 and river discharge. Regime was not re-established over the test period, but evidence from previous years when the system recovered from dredging and flood scour, and the results of this study, supports an asymptotic return to an indeterminate equilibrium position. This study adds a unique methodology to estuarine literature where studies of equilibrium restoration are uncommon. The findings could be useful in a general sense to other estuaries where sediment removal is required for efficient port or estuarine use.

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CHAPTER 3:

A FIRST ORDER MORPHOLOGICAL RESPONSE MODEL (FORM) FOR PREDICTING HYDROLOGICALLY-INDUCED BATHYMETRIC CHANGE IN COASTAL-PLAIN ESTUARIES (Kidd et al., 2016a)

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CHAPTER 4:

A SCENARIO-BASED APPROACH TO EVALUATING POTENTIAL ENVIRONMENTAL OUTCOMES FOLLOWING A TIDAL BARRAGE INSTALLATION (Kidd et al., 2015)

Abstract

Anthropogenic adjustment to estuarine environments has commonly occurred with some dating to Roman times for estuaries in the UK and Europe. Dykes, levees, weirs, infilling, causeways, jetties, bridge abutments and barrages all fit this category. Total exclusion barrages have a particularly high impact as they are permanent barriers to tidal flow. The environmental impacts of five putative barrages in various locations within the Tamar River estuary in northern Tasmania, Australia were assessed by considering likely hydrological, morphological and ecological outcomes. We found that all hypothetical barrages would produce downstream silt accretion, some to the point where a major port would become unusable without ongoing dredging. The closer a barrage was located to the mouth of the estuary, the greater the loss of tidal prism, the lower the effect of flushing by floodwaters, and the greater the loss of estuarine biodiversity. Extensive areas of dead and decaying invasive rice grass (*Spartina anglica*) in the mid estuary would increase the probability of nuisance algal blooms and contribute to greenhouse gas emissions. Constant headpond surface heights would concentrate energy from wind waves at the new fixed water level resulting in bank erosion and subsidence. Tidal wetlands in the upper estuary would be lost with the loss of tidal regime accompanying the installation of a barrage at any point along the estuary. This would contravene the international treaties protecting the migratory waterbirds which use these habitats. Installation of a barrage at the uppermost location appears to represent the best trade-off between adverse impacts and increased recreational and visual amenity. Unfortunately, barrage installation at any site within the estuary fails to address the major anthropogenic stressors of reduced riverine inflows and tidal flushing. A wider sustainability analysis is needed in which the costs of meeting environmental, social and economic objectives are considered.

Key words total exclusion barrage, remnant estuary, tidal prism, bathymetry, migratory species, morphology

1. **Introduction**

Tidal barrages, or structures which prevent marine water from moving upstream in an estuary, were installed in past decades, in many parts of the world, for many reasons. Their uses include tidal power generation, storm surge protection, storage of freshwater and provision of impoundments for recreation (Gray et al., 1992). Morris (2013) classified barrages into three categories, permeable (may be raised and lowered to protect from storm surges); sills (retain high water whilst allowing higher tides to penetrate) and causeways, which exclude tidal influence. The latter, also known as total exclusion barrages have particularly high impacts as they present a permanent barrier to estuarine excursion of tides and salt. Estuarine barrage installation has become less frequent as environmental repercussions have become better understood and the trade-offs with a range of ecosystem services are regarded as less acceptable. There is a paucity of analyses assessing the impacts of barrages in the peer reviewed literature, despite evidence of acute detrimental impacts (Morris, 2013). The United States leads the world in estuarine and stream rehabilitation, where 306 barrages or dams were removed from 1999 to 2008 (American Rivers 2008) as part of a billion dollar per annum ecological restoration industry (Bernhardt et al., 2005). Debate over the building of a major barrage on the Severn in the UK concentrated on environmental issues with arguments for (Kirby and Shaw, 2005) and against (Clark, 2006), notwithstanding that the barrage had the potential to generate an average 2 GW or 5% of UK power demands (REUK, 2009). A barrage constructed near Cardiff in Wales had a significant accretion impact on the adjacent coastal areas while causing erosion at distances up to 72km (Phillips, 2007). Salt water became trapped behind a fixed barrage on the River Lagan in Northern Ireland causing oxygen depletion and damage to the aquatic environment (Walker et al., 1996). The Marina Barrage was recently built in Singapore as a freshwater storage and to prevent low-lying areas flooding during torrential tropical downpours. The Singaporean government claim it is successful, but this may not be an accurate assessment as Xu et al. (2011) found increased levels of 13 emerging organic contaminants. The barrage truncates the estuary at the coast with no remnant estuary with which comparisons may be made. The Lower Nakdong River in South Korea is barraged to prevent salt water intrusion, but sedimentation problems and constant dredging have necessitated changes to gate operation in a bid to increase sediment flushing (Ji et al., 2011). The Wansbeck barrage in Northumberland is opened for 3 days per month during October to March in an attempt to counteract sandbar formation across the mouth (Worrall and McIntyre 2007). Behind the impoundment, sedimentation rates over 20 years to 2007 are nearly $400mm.yr^{-1}$, and algal blooms are a problem. Worrall and McIntyre concluded that the barrage was not fulfilling its objectives and the situation was only likely to get worse (2007). A barrage on the Petitcodiac River in Canada diminished the estuarine bore and the tidal prism to such an extent that the remnant estuary atrophied to 10% of the former width, and extensive salt marshes developed (Morris, 2013). The bathymetry from the head of the original estuary effectively migrated 16km to the new head of the estuary at the barrage (Kidd et al., 2016a). Siltation above the barrage also became a problem, as did erosion of the upstream banks. Flow has now been increased by opening the gates on the barrage and the width is returning to normal. A major barrage constructed at Goolwa near the mouth of the Murray River in South Australia in the 1940s to convert lakes Albert and Alexandrina to fresh water decreased the tidal prism by 85%, resulting in the mouth of the Murray becoming unnavigable within 12 months (Harvey, 1996). Sand carried along the coast by longshore drift and into the estuary by asymmetrical tides and aeolian processes settles in the remaining tidal zone (Webster 2005). This has resulted in the mouth closing completely, on average, every second year (Jenson et al., 2000; Walker, 2003). Continued significant environmental degradation is expected, caused by reduced flows, increased sedimentation and the accumulation of nutrients (Jenson et al., 2000). Any total exclusion barrage removes the upstream tidal prism which places the remnant system out of equilibrium. As a general rule, a loss of tidal prism will produce sedimentation (Dennis et al., 2000). To regain equilibrium, the remnant estuary must either increase its tidal prism, or reduce its cross-sectional area. The former requires a significant increase in the tidal range as predicted by some models (Prandle, 1980); and the latter requires a positive net sediment supply (Morris, 2013). The ASMITA model (Aggregated Scale Morphological Interaction between Tidal Inlet and Adjacent Coast) (Stive et al., 1998), is able to calculate equilibrium volumes and surface areas following sea level rise, dredging and infilling. Prandle (2003, 2004) and Prandle et al. (2006) produced morphodynamic models for different estuary types without specific reference to installation of a barrage. In an earlier paper Prandle (1980) discussed the similarities of barrage installation with AC circuit theory and modelled the likely effects on tidal ranges without specific reference to morphological effects. Van Dongeren and de Vriend (1994) produced a 1D computer model which in part simulated the effects of truncating a 20km estuary at 15km. Their interest was in tidal flats but the model also predicted atrophy of the channel, over 100 years. Bottom-up models (Emphasys Consortium, 2000) of tidal dynamics, sediment transport, salt intrusion etc. can be determined from tides at the mouth, estuarine bathymetry, river flows and bed roughness. All involve simplifications and assumptions, and are accurate over time scales of a few tidal cycles. The UK Parliamentary Office of Science and Technology (POST, 2013) cautioned that modelling always begins with a simplification of how the estuary works and, in the case of the Severn Barrage, there were a lack of comparative data available for model calibration. The assessment of morphological change due to a barrage is best modelled with a top-down approach such as a regime model (Emphasys Consortium, 2000).

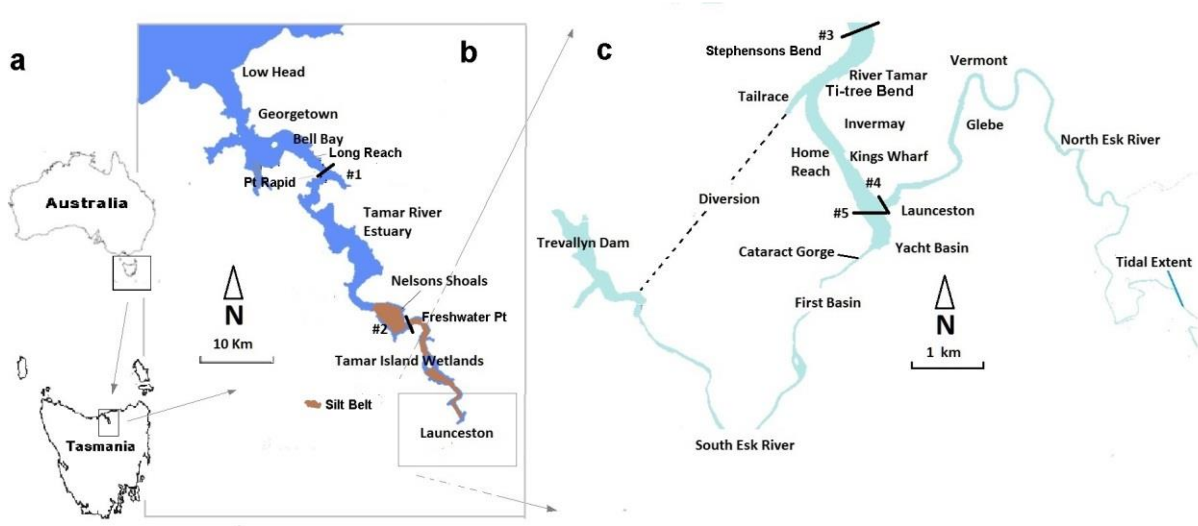

Fig. 4.1 Location of the Tamar River Estuary including putative barrage positions

Excessive silting in the upper Tamar River estuary in northern Tasmania, Australia (Fig. 4.1) has prompted calls for the installation of a total exclusion barrage (a permanent barrier to tidal flow), with the aim of addressing one of the perceived stressors (tidal asymmetry resulting in the upstream transport and deposition of flocculated silts and clay) and providing new ecosystem services based on the creation of a large freshwater lake or headpond. Although one recent proposal is for a barrage near the mouth of the estuary (~22km inland), past proposals have advocated barrages at sites further upstream. In April 2013 the Launceston Flood Authority (LFA) proposed an AU$25 million barrage across the mouth of the North Esk River (Examiner 2013), 70km from the coast and 11.5 km from the estuary head.

As well as potentially addressing the issue of excessive silt accretion, additional benefits provided by the creation of a large freshwater lake include a reliable source of water for horticultural and agricultural crops, enhanced recreational opportunities for a variety of water-based sports, enhanced visual amenity and the potential to generate hydropower. Little public discussion has occurred of the negative hydrological and morphological impacts on the remnant estuary and near-shore marine region, nor the likely ecological effects on the entire estuary.

We hypothesised that the impacts of a barrage on estuarine hydrology, morphology and ecology in the Tamar River estuary would vary with the distance of the installation from the mouth. We have used a scenario-based approach to evaluate the outcomes of tidal barrage installation at four sites along the estuary and one at the mouth of a major tributary.

2. Methods

2.1 Site Description

The Tamar River estuary has provided a convenient shipping route, fresh water, and good soils for agriculture since European settlement in 1804 (Edgar et al., 2000). The estuary, which is classified as a mesotidal drowned river valley (Edgar et al., 2000), although the upper reaches are better categorised as a coastal-plain estuary (Kidd et al., 2014). The estuary comprises three distinct waterways, the Tamar River estuary and two major tributaries, the North and South Esk Rivers. The North Esk River is tidal for 11.7km and is therefore a continuation of the main estuary. The waterways meet at the city of Launceston (population of 90,000), approximately 70km upstream of the estuary mouth. An extensive silt belt runs for ~20km downstream of Launceston (Fig. 4.1b).

The tidal range increases from 2.34m at the mouth to 3.25m at Launceston (Foster and Nittim, 1987) and is therefore hyper-synchronous (Dyer, 1997). At the mouth, tidal constituents are M_2 dominated (1.117m) followed by N_2 (0.252m), K_1 (0.161m), S_2 (0.136m) and O_1 (0.113m) (Foster and Nittim, 1987). M_4 is 0.035m and M_6 is 0.011m (Kidd et al., 2014). In the lower North Esk the corresponding constituents are: M_2 (1.432m), N_2 (0.300m), K_1 (0.042), and S_2 (0.083). The combined M_4 and M_6 constituents amount to ~0.2m (Kidd et al., 2014); indicative of asymmetrical tidal velocities. Flood tides peak at 40cm sec^{-1} and ebb tides reach 30cm sec^{-1} (Foster et al. 1986). In times of low freshwater inflows, sediment which has flocculated at the salt water boundary is carried upstream and deposited in the upper estuary ((Foster et al., 1986), Fig. 4.2). In normal flows, salt intrudes almost to the Tamar Island wetlands. However, during the recent decadal long drought, salt intruded further to Home Reach (Fig. 4.1c) and killed riparian willows (*Salix* sp.).

Fig. 4.2 Silt accretion across 250m of the upper estuary (Yacht Basin) (left) and Seaport Marina (right) in the North Esk River. The position of Barrage #5 coincides approximately with the right hand side of the first image

The North and South Esk Rivers provide many ecosystem services and benefits to the community. Drinking water is drawn from both systems while the Trevallyn dam on the South Esk River feeds water to a hydro-electric power station via a diversion tunnel. The outflow from the station meets the estuary at the Tailrace (Fig, 4.1c). The power station contributes AUS$30million annually to the Tasmanian economy, but has reduced flows through the Cataract Gorge on the South Esk River from ~$300m^3sec^{-1}$ to $2.50m^3sec^{-1}$. In 2011, the power station operators (Hydro Tasmania) increased this discharge from $1.5m^3sec^{-1}$ for environmental reasons, although the legal requirement is only $0.43m^3sec^{-1}$. Tailrace discharge averages ~$50m^3sec^{-1}$ (with an additional ~20 m^3sec^{-1} provided by an inter-basin transfer) and varies from 0 to $90m^3sec^{-1}$, depending on the number of turbines used. Services to shipping remain an important ecosystem service in the upper estuary. A ship lift facility at Kings Wharf can cater for vessels up to 250m, whilst other slipways cater for smaller fishing and pleasure craft. Other ecosystem services include salmon farming at Long Reach in the lower estuary which relies on the unpolluted, tidally-flushed marine water (TEER, 2012). Recreational fishing occurs throughout the lower to mid-estuary. Silt accretion has resulted in the loss of many ecosystem services, particularly recreational activities. A floating marina at the mouth of the North Esk River is severely affected (Fig.4.2). Rowing and sailing have been seriously curtailed, and soft mud banks represent both physical and health hazards (BMT_WBM, 2008; Seen et al., 2004).

In the early 1800s a port was established in the North Esk River, but was later moved, firstly to Kings Wharf in Home Reach as ships became larger, and finally to the deep water of Bell

Bay in the 1960s. Dredging commenced in the 1880s to provide adequate depths (Ellison and Sheehan, 2014). The upper reaches of the estuary have undergone considerable in-filling, river realignment, and canalisation (Davis and Kidd, 2012) resulting in a ~30% loss of tidal prism since settlement. This combined with the cessation of dredging has resulted in silt accretion as the estuary establishes a new equilibrium between the tidal flows and cross-sectional areas.

Effluent from a wastewater treatment plant enters the estuary opposite the power station confluence at Ti-tree Bend (Fig 4.1c), and several other sites in the upper estuary. Treatment is secondary only and in times of heavy rain, untreated sewage combined with storm water flows to the estuary.

Extensive areas of the mid-estuary have been colonised by an exotic macrophyte, the rice grass, *Spartina anglica* C.E. Hubbard. This was introduced to the estuary in the late 1940s (Sheehan and Ellison, 2004) to stabilise mud banks. However, the dense growth habit and extensive rhizome network of the species has acted to elevate the natural shoreline and reduce the habitat available for juvenile fish and other aquatic organisms. Tidal flats can create an ebb velocity bias, and the ramifications for net sediment transport (van Dongeren and de Vriend, 1994) from the loss of these flats is not well understood.

Many studies have been commissioned (BMT_WBM, 2008; Foster et al., 1986) on the silting issue, with some recommending the installation of a (total exclusion) barrage. Renewed calls for barrage installation have recently gained local media prominence.

2.2 Scenarios

We compared the impacts of placing a total exclusion barrage at each of five sites along the estuary, one at a proposed site ~22 km from the estuary mouth (Point Rapid) (Fig. 4.1b), and at four additional hypothetical locations (Figs. 4.1b & 4.1c). For each site we calculated the existing tidal prism and assessed the consequences of a subsequent barrage-imposed decrease from that point. For those scenarios sited in the silt belt (Fig. 4.1b), we considered the likely influences on upstream silt deposits and assessed the immediate and future evolution using a model developed by Kidd et al. (2016a). The model results were highly correlated with actual widths (R^2=0.89, p<0.001).

2.3 Model description

The morphological model is a top-down regime model (Emphasys Consortium, 2000), based on a funnel shaped estuary where the width from the head can be represented as a power function of distance (Hood, 2002; Prandle et al., 2006). The equation derived was $y=4.6*10^{-6}x^{1.54}+20$ using the head of the tidal North Esk as the starting point. The constant 20 is the width of the riverine North Esk. Kidd et al. (2016a) calculated tidal cross sectional areas from the product of the width equation and tidal range equation, and subsequent integration gave the tidal prism. Tributaries and storages were added to the model by addition of the tidal prisms. Their final model and data points are in Figure 4.3, with $R^2=0.89$ over 32 km of the upper estuary.

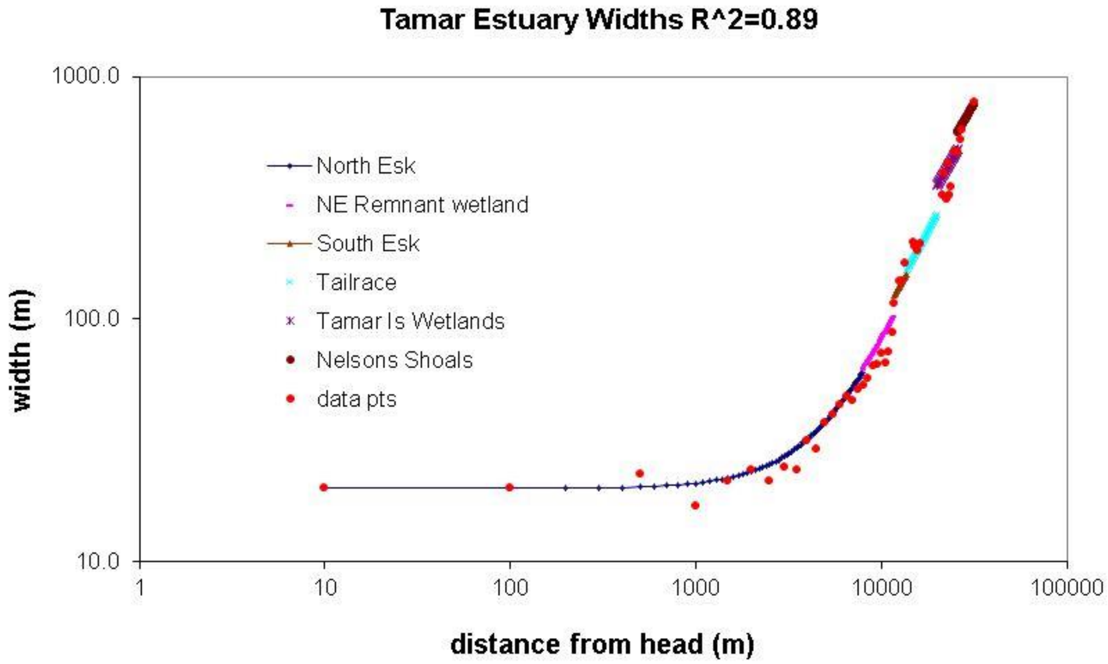

Fig. 4.3 The upper Tamar River estuary as modelled by Kidd et al. (2016a) showing tributaries and storages added as point sources. This is a classic funnel-shaped estuary with a starting width of 20 m

Scenarios #1, #2 and #3 required an adjustment to the riverine width in the model to 152 m which accounts for the greater freshwater discharge of the new starting point (which includes the Tailrace outflow). This width is that predicted by the model downstream of the Tailrace confluence, which includes ~3,000,000 m^3 of tidal prism. It also approximates the width of the Tailrace mouth, which includes 175,000 m^3 of tidal prism, so 152 m is a generous approximation of the width of the head of the remnant estuaries #1, #2 & #3, with no tidal volume. The seaward barrage (#1) is in the ria section of the estuary, which is outside the extent of the model. Morris (2013) cited examples where rias were transformed to coastal-plain estuaries with extensive salt marsh and intertidal areas following barrage installation.

We have therefore applied the concept (model) to this barrage over 10 kms to the port at Bell Bay, noting that (as with the Petitcodiac River) the confines of the ria are no longer a barrier to the width of the remnant estuary. We have also made a qualitative assessment using analogues of existing barrages. Likewise, infill times for the remnant estuary were estimated using existing models (Prandle, 2004; Todeschini et al., 2008). We used the difference in tidal heights between Low Head and Launceston to calculate the heights of the lake (headpond) created by each barrage (AUS_168, 2012). Heights are Australian Height Datum (AHD) (Fig 4.4).

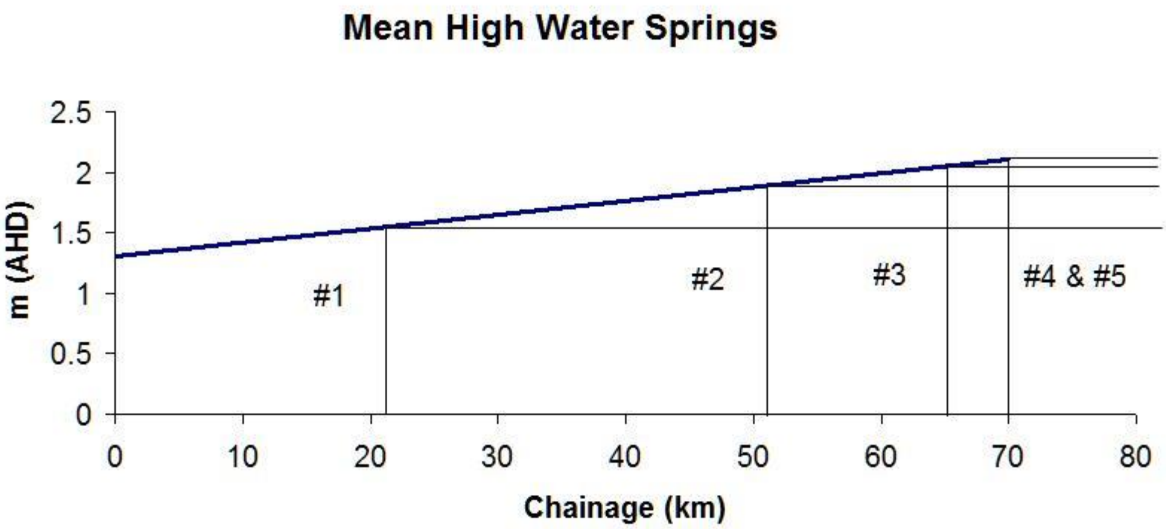

Fig. 4.4 Mean high water spring (MHWS) tides as predicted from AUS_168 (2012) for Low Head (0km) to Launceston (70km). Assuming a linear increase in tidal height then the graph gives the height of each headpond in Launceston

We used the modified O'Brien's equation ($A = 3.1*10^{-3}*P^{0.81}$ where: A is the cross sectional area (m^2); and P is the tidal prism (m^3)) (BMT_WBM, 2008; O'Brien, 1931, 1966) to calculate the cross-sectional area (x-area) to which the water-body will atrophy downstream of each putative barrage location, as it seeks to attain equilibrium with the new tidal prism. We have made some predictions on the effectiveness of flood scouring on sediment transport. We have assumed that tidal constituents and tidal ranges do not alter with installation of a barrage, although in reality continuous change is likely to occur until regime is re-established in the remnant estuary.

Figure 4.5 provides a conceptualization of our model. The model is less linear than the figure suggests, with allowances for variation in the tidal range, width varying to a power of distance, addition of storages, tributaries and channels. In an idealised uniform estuary the eventual bathymetry downstream of each barrage will be identical. The tidal prism falls to zero immediately downstream of a barrage and further contraction will also be felt at each point downstream and so the initial reductions are only a fraction of the final equilibrium position. For the two extreme conditions illustrated in Figure 4.5 (no barrage and a barrage across the mouth of the estuary) this holds true. For a barrage at the mouth, the distance *d* becomes the length of the estuary (or the extent of the model) and the whole of the tidal prism is removed. We can assume therefore that the model also holds true for any length *d* which is less than the length of the estuary. The eventual tidal prism loss will be given by volume B. The morphological impact of barrage #5 is modelled by applying a tidal prism of zero for the South Esk River (at x=11700m) to the model.

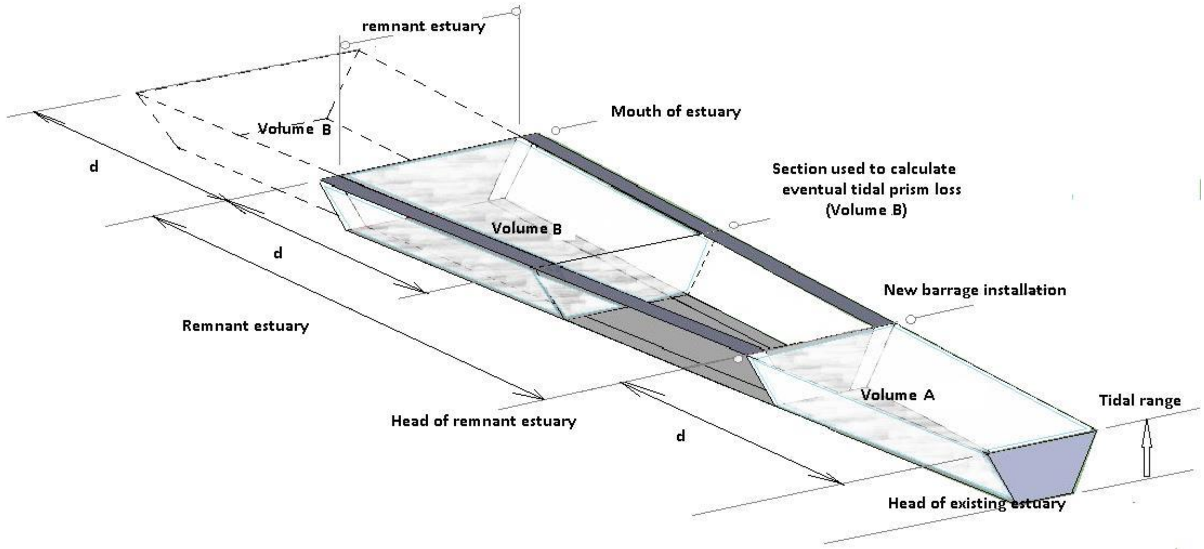

Fig. 4.6 Conceptual model of the effect on tidal volumes of installing a total exclusion barrage at a distance *d* from the head of the estuary. Volume A is the immediate tidal volume lost to the estuary due to the barrage, whilst the extrapolated volume B is the total volume lost from the estuary in the long term, as the system adjusts to a new regime commensurate with the loss of volume A. The model is true for the two extremes; a barrage at the mouth where volume A is the whole tidal prism, and no barrage where A and B = 0. For simplicity width is shown increasing linearly with length but the concept applies equally to an estuary where width is a power function of length. Volume B is estimated by the Kidd et al. (2015)

model. (Volume B-volume A) is the volume of sediment accreted onto the intertidal banks of the remnant estuary

3. Results

Our assessment of the morphological impact of barrage #1 on the lower estuary (Bell Bay) is summarised in Table 4.1, which shows a large diminution over decadal time scales. A summary of the likely impacts of a barrage installed in the lower (#1), mid (#2) and upper (#3 & #4) estuary on hydrology, sediment deposition, and ecology are summarised in Table 4.2. The morphological effects of barrages #2, #3 & #4 are shown in Figs. 4.6 & 4.7. The contraction of the tidal prism to a new regime is evident downstream of each barrage and this translates to a commensurate contraction of the estuarine cross-sectional area, as per the modified O'Brien's equation (BMT_WBM, 2008). The contraction is greatest for the downstream barrages.

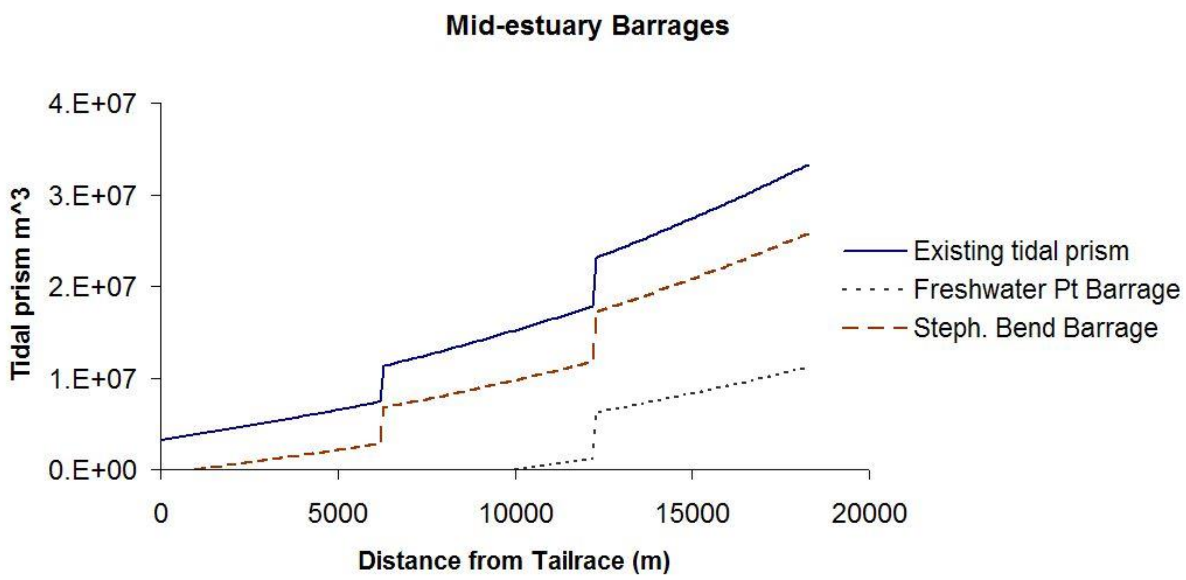

Fig. 4.6 The impact of mid-estuary barrages (#2 & #3) at Freshwater Point and Stephenson's Bend compared with the existing tidal prism. The tidal prisms of Tamar Island Wetlands and Nelson's Shoals are entered as point sources

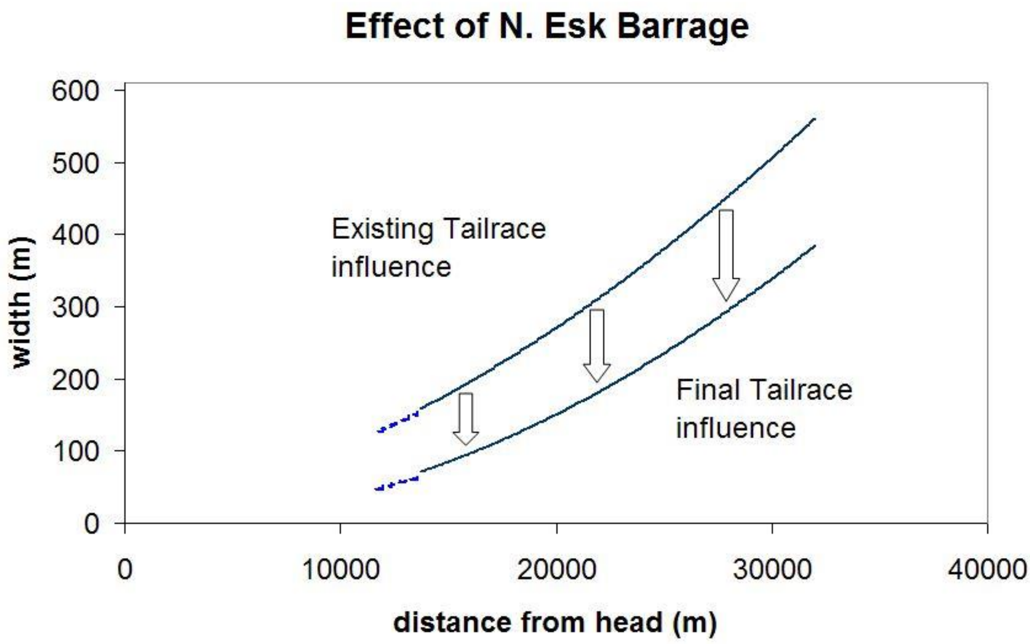

Fig. 4.7 The effect on estuarine widths due to a barrage (#4) across the North Esk River mouth. Tamar Island Wetland and Nelsons Shoals storages are not shown. The contraction represents accretion of $3.8*10^6 m^3$ of silt on the tidal banks and $12*10^6 m^3$ when the channel is included

Table 4.1

Tidal prism and x-area predictions at the major port (Bell Bay) for a barrage installed 10km upstream (Long Reach). The predicted x-area contraction at Bell Bay to 9.2% of original is similar to that observed for the Petitcodiac River (~10%) (Morris, 2013; Van Proosdij et al., 2009)

Model	Original Tidal Prism (m^3)	New Tidal Prism (m^3)	Original X-area (m^2)	New X-area (m^2)	% of Original X-Area
Initial Loss	152,000,000	50,000,000	13,140	5350	40.7
Kidd et al.	152,000,000	8,000,000	13,140	1210	9.2

The situation at barrage #5 differs from the others because this cross-section is not part of the main estuary. The model shows that the long term impact from the removal of the tidal prism of the Yacht Basin (325,000 m^3) at ~2 km downstream of barrage #5, will be contraction of the tidal prism from 3,200,000 m^3 to 2,700,000 m^3, and a reduction in the x-area from 576 m^2 to 502 m^2 (Fig 4.8).

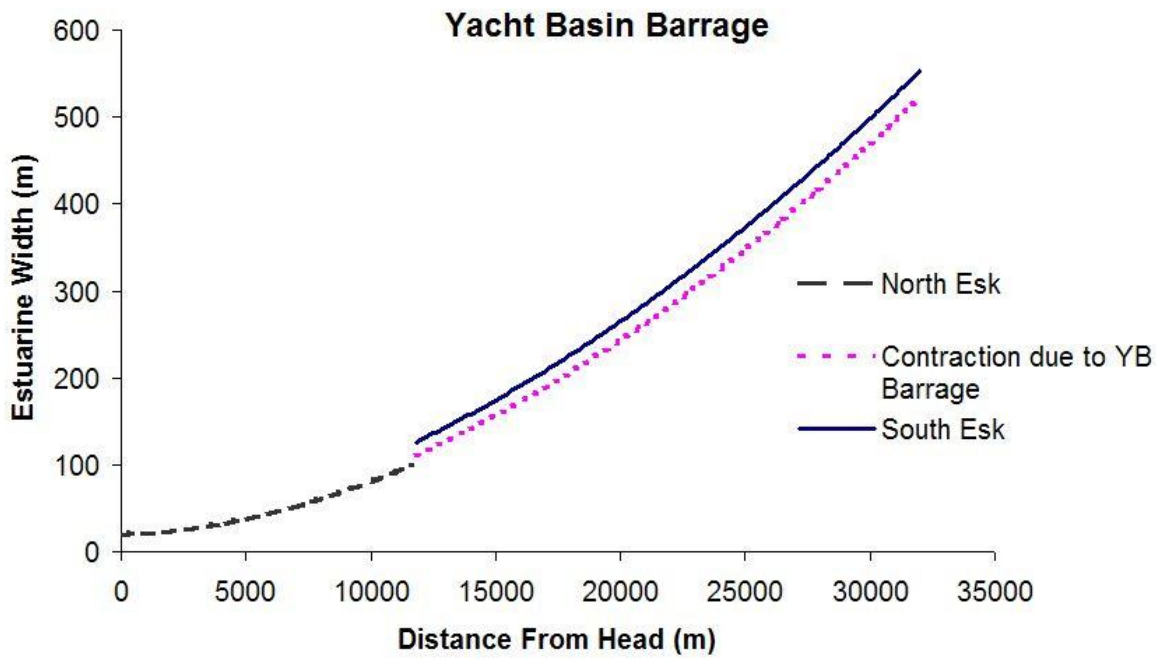

Fig. 4.8 Width contraction due to barrage (#5) across the South Esk River, resulting in 790,000m^3 of sediment accretion over the silt belt

4. Discussion

4.1 Morphology

The effect of installing a total exclusion barrage is to move the head of the estuary to that point. As a consequence the barrage located closest the mouth of the estuary (#1) will have the greatest negative impact on the major port (Bell Bay) with a likely >90% reduction in the x-area (Tab 1). This would render the port unusable by most shipping traffic. In comparison, the uppermost barrages (#4 and #5) will have the least impact on the x-area of the downstream port.

As with the stressors identified by Davis and Kidd (2012), any barrage is a major stressor applied to the system, and reduces the tidal prism significantly, notwithstanding that the opposite is the case in the Texel Inlet in the Netherlands (Elias and van der Spek, 2006). However this is not a single channel system and is an inappropriate analogue with the Tamar.

Barrage #1 is outside the range of the model but its' use is justified on several counts. Firstly, all barrages move the head of the estuary to the location of the barrage. Secondly, the situation is similar to the Petitcodiac River in Nova Scotia where the bathymetry has migrated ~15 kms due to the Moncton Barrage converting the remnant estuary to that of a coastal-plain (Kidd et al., 2016a). Similarly for barrage #1, the remnant estuary is presently confined by the geology but the loss of 10^8 m^3 of tidal prism puts the bathymetry at regime within those limits. The new regime is likely to take a century to establish with an atrophied channel and extensive saltmarsh. Turbidity below the barrage is low due to the lack of fine sediment which is generally trapped in the upper estuary and marine sediment is more likely to be the constituent of any geomorphologic change. We have used analogues with existing barrages, as suggested by Morris (2013).

Table 4.2 Summary of likely impacts above and below barrages installed in lower (#1), mid (#2 & #3) and upper estuary (#4 & #5). See Rissik (2014) for a comprehensive review of the impact statement pertaining to the proposed barrage #1

Zone	Lower Estuary Barrage	Mid Estuary Barrage	Upper Estuary Barrage
1	Major tidal prism reduction Possible coastal effects	Negligible ecological effects	Negligible ecological effects
2	Major tidal prism reduction Flocculated and marine sediment accretion Fish farm affected by reduced flushing and working area Stratification likely Major mortality of estuarine adapted biota Increased abundance of freshwater species	Significant tidal prism reduction Minor increase in sedimentation Minor impact on estuarine-adapted biota Minor impact on fish farm	Small loss of tidal prism No noticeable ecological effects
3	Tidal influence removed Fine sediment accretion Scouring during major flooding	Substantial tidal prism loss Minor increase in sedimentation Minor impact on	Small loss of tidal prism Negligible ecological effects

	Major mortality of estuarine adapted biota Mortality of introduced rice grass Increased abundance of freshwater species	estuarine-adapted biota	
4	Tidal influence removed Fine sediment accretion Scouring during flooding Mortality of estuarine-adapted biota Mortality of introduced rice grass	Substantial tidal prism reduction Flocculated sediment accretion; fine sediment accretion behind barrage Scouring during moderate floods Mortality of estuarine-adapted biota Increased abundance of freshwater species Mortality of introduced rice grass close to barrage	Small loss of tidal prism Minor ecological effects Some mortality of introduced rice grass
5	Tidal influence removed Some fine sediment accretion Flood scouring Ground water issues Minor change to fauna and flora Total loss of upper estuary wetlands	Loss of tidal prism Fine sediment accretion Flood scouring Minor change in flora and fauna Upper estuary wetlands affected by fixed water levels	Reduced tidal prism downstream of barrage Flocculated sediment accretion; Fine sediment accretion behind barrage Flood scouring Minor ecological impacts

The geological confines of the ria at this barrage support an analogy with La Rance barrage in France, although it is not a total exclusion barrage. However, approximately 20 km upstream, Le Chatelier lock built in 1830s is a total exclusion barrage and caused atrophy of the downstream channel similar to the Petitcodiac River (Van Proosdij et al., 2009). The Windsor causeway on the Avon River in Nova Scotia has primarily a marine sediment regime and is a total exclusion barrage. The geomorphologic response has been erosion above the barrage

(Morris, 2013) and accretion below it (Van Proosdij et al., 2009). The model of van Dongeren and de Vriend (1994) supports this outcome with substantial accretion below a barrage placed 15 km into a 20 km estuary.

Following the cessation of dredging activities some years ago, and despite silt raking in October 2012 and the winter months of 2013 and 2014, the upper Tamar estuary is close to a state of equilibrium. Equilibrium (or regime) is that state to which the estuary naturally evolves if undisturbed. It involves a balance between the water-body cross-sectional area and the tidal volume upstream of that cross-section (O'Brien 1931) and a zero net sediment transport (Dyer, 1997). As the water body and the volume of silt are mutually exclusive, then the balance is also between the tidal volume and the volume of accreted silt on the banks. In the upper estuary, equilibrium also establishes a constant mean ebb tide velocity of ~0.25 m/sec. Any barrage installation will deleteriously alter that equilibrium.

The main stressors responsible for excessive siltation in the upper estuary have been previously identified as the diversion of freshwater inflows by a hydro-electric power plant and a 30% reduction in the tidal prism caused by channel re-direction and infilling of tidal wetlands for urban development (Davis & Kidd 2012). The loss of tidal flats (canalisation) was instrumental in producing the flood dominant tides which now prevail (Dronkers, 1986; Friedrichs and Aubrey, 1988). The negative impacts associated with a reduction in tidal flushing will be greatly enlarged by the installation of a total exclusion barrage, which acts to eliminate tidal flow.

Barrages #1 & #4 have been proposed to 'address the problem of asymmetrical tides', but such tides have no influence at equilibrium, and are not a stressor on the system (Davis and Kidd, 2012). Further, Dyer (1997) infers that the flood tide dominance of the upper estuary is a natural response to historical dredging, and Todeschini et al. (2008) claim that tidal asymmetry decreases as the system approaches equilibrium (for an estuary without river discharge). It is ironic that reducing the equilibrium position by installing a barrage brings asymmetrical tides into the equation, as one mechanism by which the system evolves to the new equilibrium (Dronkers, 1986). Van de Kreeke and Robaczewska (1993) attest that tidal asymmetry does not guarantee net bed-load transport of coarse material. However, for fine suspended sediment, the proposal (and all others) activates the very mechanism it purports to nullify.

4.2 Turbidity

The existing bathymetry provides some indication of the sediment regime downstream of any of the putative barrages. The South Esk River provides the bulk of the freshwater input to the system but this meets the estuary at natural barriers to tidal incursion at the Cataract Gorge and at the power station outflow. At these barriers the turbidity is low as the freshwater discharge prevents incursion of the turbid estuarine water. The cross sectional area of each water body is governed by discharge at low tide, which acts as a foundation for the tidal volume. For the Tailrace the low tide cross sectional area (~500 m^2) is commensurate with a discharge of ~50 $m^3 sec^{-1}$ flowing at ~0.1 $m.sec^{-1}$. Turbidity remains low until the flow mixes with turbid estuarine flow near the estuary confluence. A bathymetric survey of the tidal Cataract Gorge (Fig. 4.1) shows it is free of fine sediment (pers. obs.) for ~500 m. Similarly the Tailrace suffers no accretion problems for its entire length. A similar low turbidity zone can be expected immediately downstream of each of the putative barrages, with a greater effect for those barrages with a greater freshwater flow (#1, #2 & #3).

4.3 Change in groundwater regime

The installation of a barrage at any site along the estuary will produce a headpond elevation the same as the high tide at the barrage and elevate groundwater heights in the now drained tidal flats of the upper estuary (Fig. 4.4). As a consequence groundwater will affect an existing suburb (Invermay) parts of which are 600mm below high water springs level (HWS). Groundwater heights are currently controlled by releases to the estuary at low tide, but this mechanism will not be available with a permanent headpond height near existing HWS. Although this issue could be mitigated with strategic engineering (Heathcote et al. 2003) this will add to the economic cost of a barrage installed at any location along the estuary.

4.4 Bank erosion

In a tidal environment the energy from wind waves dissipates over the entire intertidal bank. In the permanent freshwater headpond created by a barrage this ‘intertidal’ range will tend to zero. Constant lake heights concentrate energy from wind waves at the fixed water level. This will result in bank erosion and subsidence, and will be a problem for each of the hypothetical lakes. The effect was evident for all installations examined by Morris (2013). In the mid estuary, where extensive banks of invasive rice grass are present, banks of dead and decomposing plant material (caused by the change in salinity), may provide a short term buffer to erosion. However, over time, erosive effects will be important at all locations.

4.5 Impact on hydropower generation

Any solution involving the creation of a permanent high water level in the hydropower plant outflow will cause a reduction of the efficiency of generation because the effective head is reduced. Turbines installed on a barrage can only recoup the energy lost in this process and so any gain or advantage in electrical energy output from a barrage installation in the Tamar River estuary will be due to net discharge over that of the power station outflow. Such turbines are not tidal energy turbines; they have very limited operational hours and provide no justification for the installation of any of the barrages discussed. However, turbines installed in the upper estuary (#3) have the advantage of a higher tidal range (3.25 m compared to 2.58 m at #1) with very little difference in the fresh water over-spill. When evaporation and other losses are considered Barrage #3 would provide the best hydropower option.

4.6 Loss of tidal wetlands

A barrage at any point in the estuary will remove the magnification of the tidal heights further up the estuary. Barrage #1 will create a headpond at 1.5 m AHD, 0.6m lower than HWS level in Launceston, (2.1 m AHD). This will result in the loss of the remaining tidal wetlands in the area in the upper North Esk. As the barrage position progresses up the estuary the resultant lake heights will increase with a final height of 2.1 m AHD at #4 & #5.

4.7 Impact on sedimentation

When a system is out of equilibrium due to the flow being too low to support the x-area, silting will occur at a rate which is dependent on the concentration of suspended sediment (Foster et al 1986). The quiescent waters of a lake created by a barrage will trap suspended sediments behind the barrier. This will be greatest for the largest lake (i.e. behind barrage #1). This can be addressed by installing a gate which can be opened during floods to allow sediments to be flushed downstream. Some suspended sediment will spill over the barrage, even under non-flood conditions because of bank erosion caused by windage on the lake surface, boat wash and land run-off. The transported sediment will flocculate when it interacts with the salt water below the barrage. In times of average to low flow, each barrage will trap sediment behind it and, in the absence of floods, will eventually fill.

Downstream of each barrage, accretion will occur due to the equilibrium imbalance. Morris (2013) found this in each of the barrages he discussed. For barrages #3, #4 and #5, sediment concentrations immediately downstream will decline due to the flocculated salt water component reducing as a percentage of total flows (4.2). Barrage #1 is downstream of the existing silt belt, where presently low suspended sediment concentrations exist. This barrage can only increase this concentration, as the flocculation zone is moved and asymmetrical tides transport flocculated and marine sediment upstream to the barrage.

4.8 Salt water intrusion

The volume of the largest lake (created by barrage #1) above the present low tide is 100,000,000 m^3 and, with an inflow of 2000 m^3sec^{-1} (due mainly to flooding of the South Esk), would take ~ 14 hrs to fill. Opening a floodgate in barrage #1 during a 2000 m^3sec^{-1} flood would allow salt water to flow into the lake. A potential conflict exists as to whether fresh water storage should be preserved when a flood is imminent, or whether scouring potential takes precedence over increased salinity. The Wivenhoe Dam on the Brisbane River in Queensland provides an example of where the original objective had become skewed over time. The dam was built for flood mitigation and water storage (Hegerty and Weeks, 1986) but after years of drought the emphasis changed to one of water storage, with catastrophic results during major flooding in 2011 (Chanson, 2011).

4.9 Flushing by flood waters

Sediment flushing during floods could never be 100% successful, resulting in some sediment remaining in the remnant estuary to again be transported upstream on asymmetrical tides. Since the major flood of 1929 (4,250 m^3sec^{-1}), 95% of floods have been less than 2,000 m^3sec^{-1} (Foster et al 1986), which is sufficient to scour a cross-section to 5,000m^2, assuming a velocity of 40cm sec^{-1} and a base of unconsolidated silt. As the lake discharges the cross-section will be such that a 2,000 m^3sec^{-1} flood will not be sufficient to maintain a flow of 40cm sec^{-1}, which is required for erosion to occur. At present, the x-area at #1 is 9360 m^2. Thus for the velocity to be greater than 40cm sec^{-1}, the discharge must be at least 3744m^3sec^{-1}. This indicates that a 2000 m^3sec^{-1} flood will not be sufficient to erode sediment deposits in the lower reaches of the lake (#1). A constant freshwater flow of 2000 m^3sec^{-1} with a velocity of 30 cm sec^{-1} provides an upper limit to the equilibrium x-area downstream of #1 at 60% of the present area. The dynamic equilibrium position would oscillate between 60% and 9% (Tab. 4.1) of the existing x-area with the long term trend at the lower end of the range. Any flood would have an effect in the atrophied cross section of the remnant estuary, immediately downstream of the barrage, in the same way as floods scour the existing upper estuary. Such a flood offers no net gain over the present condition. In normal flow conditions, all barrages have an adverse impact on the x-area at the major port downstream of #1 (Bell Bay).

4.10 Ecological impacts

The most recent assessment of ecosystem health indicated that conditions along the estuary ranged from very good near the mouth to fair near the head (TEER 2012) (Fig. 4.9). Edgar et al. (2000) considered the Tamar River estuary to have the highest conservation value of Tasmanian estuaries within its class (mesotidal drowned river valley) based on the faunal attributes of the lower estuary. It is important that any barrage installed with the objective of improving the condition of the environmentally degraded upstream section does not result in a decline in the remainder of the estuary. However, barrages #1- #4 will convert a major portion of the estuary to a freshwater lake, with the associated loss of all estuarine biodiversity.

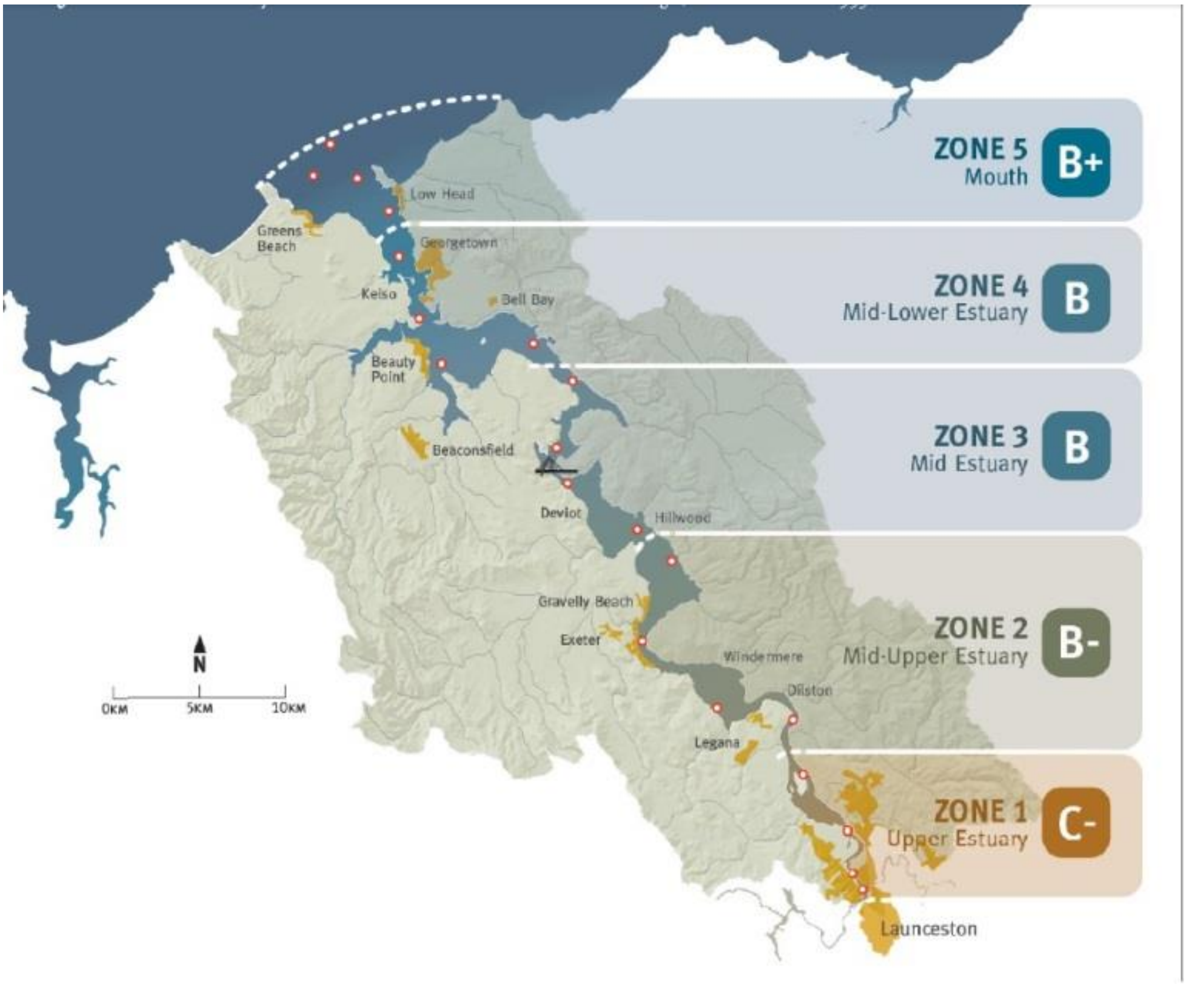

Fig. 4.9 TEER (2012) report card showing comparative health levels of various sections of the estuary

Barrages installed at locations #1 and #2 will flood and kill extensive stands of the exotic grass, *S. anglica*. This is a potentially positive outcome because widespread invasion has resulted in the loss of estuarine habitat through the conversion of previously extensive mudflats to drier rice grass meadows. However, the total area covered by the rice grass (~ 8km^2) will create a significant amount of dead and decaying organic material. This will release large amounts of CO_2 and methane, with associated greenhouse effects. Large amounts of decomposing organic material will result in dissolved oxygen depletion during warmer summer periods. The accompanying release of nutrients, combined with a lack of flow, will potentially trigger large algal blooms. To date the rice grass has stabilised >1.0x10^6 m^3 of silt (Sheehan and Ellison, 2014) the prognosis for which is uncertain. If it were to stay in-situ, then a new freshwater lake offers little additional amenity to recreational users and would cause increased turbidity on exposed fetches.

Secondarily treated sewage effluent will flow directly into lakes created by barrages #1- #4. This would further increase the risk of nuisance algal blooms and would need to be addressed by upgrading wastewater treatment plants.

Tidal wetlands in the upper estuary provide important habitat for migratory species which are protected by the Japan Australia Migratory Bird Agreement (JAMBA) and the China Australia Migratory Bird Agreement (CAMBA). The loss of inter-tidal mudflats, and stabilisation of water levels to less than the existing maximum caused by barrages #1- #4, would result in the loss of the upper estuarine wetlands which provide the major habitat for these species in this region.

Fish which currently inhabit the estuary would be affected in a number of ways by the installation of a total exclusion barrage. The greatest impact is on biodiversity, with those species which are resident in the estuary, and adapted to a variable salinity regime, being replaced by freshwater species. Marine species use the estuary as a nursery area, those which move into the estuary to feed and those which pass through the estuary on spawning migrations would all be adversely affected unless fish passes are installed. The impact on marine and estuarine adapted species will be greatest with barrage #1 and least for barrage #5.

Presently the lower estuary is well mixed, but this could change with freshwater entering from barrages #1 or #2. Stratification is likely to develop as the fresh water from the barrage meets the slow moving deep salt waterbody below the barrage.

4.11 Evaluation of trade-offs in ecosystem services

PIANC (2011) identified working with nature as the best way to achieve win-win outcomes for the environment and proponents. Site-specific characteristics of the ecosystem should be fundamental to the project objectives to deliver environmental protection restoration and enhancement outcomes utilising natural processes to their full potential. All barrage options will result in changes to estuarine hydrology, ecology and sediment transport that are likely to outweigh the perceived environmental benefits, and do not satisfy the criterion of working with nature. All will produce downstream silt accretion, some to the point where the major port would become unusable as a deep water port without expensive and ongoing dredging. The closer a barrage is located to the port, the greater the silt accretion, the lower the effect of flushing by flood waters, and the greater the likelihood that existing tidal wetlands in the upper estuary will be lost. Extensive areas of dead and decaying rice grass will contribute to greenhouse gas emissions, saltwater entrapment is a real possibility, and saltwater intrusion is a potential operational conflict. Installation of a barrage at location #5 appears to represent the best trade-off between adverse impacts and increased recreational and visual amenity. It is likely to have the least impact on the estuary, with an almost undetectable effect on hydrology and sediment transport at the mouth (Tab. 4.2). The freshwater lake formed would be visually appealing, turbidity would be greatly reduced and the mud banks currently visible at low tide would be permanently covered. The amenity once provided by the upper estuary would be largely restored. However the reduction in the cross-area immediately downstream would affect an existing commercial facility (a ship lift) which requires at least the existing 550 m^2 x-area.

Proponents of a barrage at Point Rapid (barrage #1) claim their barrage is worth AU$550million annually to the local economy (www.examiner.com.au 2013 b) but neither the monetary nor environmental costs are mentioned. A benefit cost ratio (BCR) has not been calculated, modelling is incomplete, and public opinion is polarised. In a report commissioned by Natural Resource Management North (NRM North) Rissik (2014) identified major ecological obstacles to the successful implementation of the barrage.

Many countries, including Australia, are embracing the concept of ‘like for like’ biodiversity and ecosystem services offsets (Burgin, 2008; Kiesecker et al., 2009; McKenney and Kiesecker, 2010). Off-setting the ecological shift caused by a barrage installation is a formidable undertaking, perhaps approaching the magnitude of the initial project.

4.12 Timescales

The equilibrium position is determined once the barrage is commissioned; however, the rate of silt deposition will depend on prevailing estuarine, marine and possibly aeolian processes. Downstream of a barrage, suspended flocculated sediment concentrations are diluted because the fresh water component remains constant, whilst the estuarine component is depleted due the reduction of the tidal prism. Contrary to customary assumptions, sediment concentrations do not affect the equilibrium position (Prandle et al., 2006) but affect the rate at which the system attains the equilibrium position (Foster et al., 1986). Assuming concentrations are constant, the rate at which a system approaches equilibrium is proportional to its distance from it (Howard, 1965). For a system at equilibrium the rate of sediment accretion is zero and this can only increase when a barrage is installed, regardless of the sediment concentration. Sediment coring in UK estuaries shows a dominance of marine sediment over fluvial deposits (Prandle, 2004). The model developed by van Dongeren and de Vriend (1994) showed how the truncation of a 20km estuary at 15km produced an immediate reduction in channel size at the barrier and that after 100 years, the cross sectional area would still be decreasing throughout the remnant estuary by accretion of marine deposits. This is likely to be the case for the lower estuarine barrage #1, given the volume required is multiples of $10^6 m^3$, but is unlikely to apply to upper estuarine barrages (#3, #4 and #5) where an estimated >10 million m^3 of fluvial silt has accumulated over 200 years (Foster and Nittim, 1987); a redistribution of which seems inevitable as flood-dominant tides will persist.

4.13 Infill times

Several models predict the infill times for estuaries. Todeschini et al. (2008) developed an infill equation which depended on sediment flux at the mouth, depth at the mouth, sediment porosity and length of the estuary. Prandle’s (2004) model assumed that a fine marine sediment supply existed, with the rate of supply determined by the flushing time of salt. Times ranged from decades for shallow estuaries with high tidal ranges to millennia for deep estuaries with small tides (Prandle, 2004).

4.14 Other models

Bottom-up models in the literature (Emphasys Consortium, 2000) predict bathymetry at equilibrium for various estuarine types (Dyer, 1997; Prandle, 2003, 2004, 2013; Prandle et al., 2006; Syvitski and Saito, 2007; Todeschini et al., 2008). Tidal forcing is the common driver in the models but each has assumptions, such as friction, channel profile, synchronicity, convergence, river flow, over tides, depth, salt intrusion, sediment concentrations, stratification and geological effects. For funnel shaped estuaries, width equations in the form exp-f(x) are derived where x is the distance from the mouth. Bottom-up models are not good predictors of long term morphology as errors are compounded over each tidal cycle (Emphasys Consortium, 2000).

Top-down models such as the regime model we have used, provide an accurate prediction of regime at the final regime state (Emphasys Consortium, 2000). However, using a combined approach, bathymetric ranges for remnant estuaries can be estimated with sufficient accuracy to assess whether a project should progress to the next phase.

5. Conclusion

Estuarine barrages are proposed and built for the best of intentions, to improve visual amenity, flood mitigation, freshwater supplies and electricity generation. However, all installations come with trade-offs needing careful evaluation. The major objective for installing a barrage on the Tamar River estuary is to address silt accretion in the upper reaches of the estuary. Evidence from other installations, together with the data presented here, suggests that this would result in adverse environmental impacts and declining ecosystem services throughout the estuary, and that these worsen for barrages closer to the coast. The main justification for barrage installation has been based on the argument that excessive siltation is due to asymmetrical tides transporting flocculated sediments upstream to where they are deposited in an area highly valued for its visual and recreational amenity. However, this is a natural process which has likely always existed in the estuary, with the net upstream transport of sediment only occurring in periods of low flow (seasonal summer droughts and a recent decadal length drought). A barrage in the Tamar estuary is the antithesis of the required sustainable remediation strategies, which as an imperative and first prerequisite, must improve the equilibrium position. We suggest that rehabilitation must address the major stressors which have been previously identified as anthropogenic changes to riverine inflows and tidal flushing (Davis and Kidd 2012). Our analysis provides a starting point for a wider sustainability analysis in which environmental, social and economic objectives should be considered.

6. Acknowledgements

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CHAPTER FIVE:

TOTAL EXCLUSION BARRAGES AS SEA-LEVEL RISE MITIGATORS: THE MORPHOLOGICAL TRADE-OFFS FOR NEW INSTALLATIONS

Abstract

Sea-level rise presents a looming problem for estuarine management and barrages of various types are part of the tool-kit of possible mitigation strategies. Evidence from existing installations shows that the morphological impacts of total exclusion barrages (TEBs) can be severe and few if any meet their design goals. We applied a previously developed regime model (FORM) to four existing TEBs (Moncton and Windsor in Canada, Tees Barrage in the UK and Le Châtelier in France), and demonstrated how it effectively modelled regimes before and after barrage installation. The model demonstrated a downstream non-linear 'bathymetric migration' as a new regime is established with the barrage at the head of the remnant estuary. Linear regression results showed a high correlation ($R^2 \sim 0.85$) with a trend-line slope > 0.9 (when y intercept was forced to zero) between widths of the before and after regime states for the simplest of the systems (the Petitcodiac); whereas the Tees was still in transition. Analyses of the other two systems is mostly qualitative but were consistent with the results from the Petitcodiac. The model predicted similar adverse morphological change for each of the barrage scenarios which was confirmed by the observed changes. Although all would act to mitigate sea-level rise in the headponds, tidal range increases in the remnant estuary would exacerbate sea-level rise.

We conclude that results do not justify any of the TEBs suggested for various sites in the Tamar River estuary in Tasmania. The objective of mitigation of both sea-level rise and excessive silt accretion must be carefully evaluated against adverse tidal, morphological and environmental consequences.

Keywords

Regime, equilibrium, total exclusion barrage, estuarine model, sea-level rise

1. Introduction

A large percentage of the world's population live around estuaries (Cohen et al., 1997; Small and Nicholls, 2003) and the looming threat of sea-level rise is a major management issue, in terms of safety and protection of infrastructure (Aerts et al., 2014). Sea-level rise (SLR) may be due to iso-static influences, natural climatic variation, or as an inevitable consequence of anthropogenic global warming. The effect of the latter is twofold; expansion of the oceans due to higher water temperatures and the influx of freshwater from melting land born ice. At the geological time scale, sea-levels have fluctuated over many tens of metres and levels 130

000 years ago were several metres above those of the present (Overpeck et al., 2006). During the last inter-glacial sea-levels were between 5 and 10 metres higher than present day levels (Church et al., 2013). The International Panel on Climate Change (IPCC) predict sea-levels to rise by between 2.8 ± 0.8 and 3.2 ± 0.4 $mm.yr^{-1}$ over the next century (Church and White, 2011), exposing a huge proportion of the world's population to storm surge flooding (Aerts et al., 2014). Over the past centuries the canalisation of many estuaries has allowed agricultural and urban development on inter-tidal flats which are below sea-level and are now particularly vulnerable to SLR. In the Canadian Provinces of Nova Scotia and New Brunswick, total exclusion barrages (TEBs) were built in the late 1960's to protect the tidal levee infrastructure (Van Proosdij et al., 2009) at Windsor and Moncton respectively.

The adverse effects of TEBs are becoming clearer (Jenson et al., 2000; Ji et al., 2011; Kidd et al., 2015; Kirby and Retiere, 2009; Kirby and Shaw, 2005; Morris, 2013; Phillips, 2007), but they continue to be proposed for some estuaries. A TEB on the Ems River estuary at Herbrum in Germany, together with on-going dredging of the channel, increased the tidal range by ~2.5m (de Jonge et al., 2014; Schuttelaars et al., 2013), exacerbating any effect of sea-level rise in the remnant estuary. This paper assesses the suitability of TEBs to mitigate sea-level rise by consideration of the morphological impacts of four existing TEBs, and by inference, the suitability of such a structure for mitigation of sea-level rise in the Tamar River estuary in Tasmania Australia. We evaluate the bathymetric change which has occurred in each estuary and assess the effectiveness of the first order morphological response model (FORM) developed by Kidd et al. (2016a) to model each change, and by inference, its' suitability for use in the Tamar River scenarios.

1.1 Modelling

Bathymetric change results in a local adjustment of the tidal prism, tidal dynamics, salinity and sediment flux (Prandle, 2009). Careful modelling is required to elucidate in detail the subsequent processes of siltation and erosion which occur but as a basic rule reductions in tidal volume (tidal prism) lead to silt accretion and vice versa (Dennis et al., 2000). Given that the tidal prism is generally considered to be the volume of water between low and high tides (O'Brien, 1966; Seabergh, 2006; Stive et al., 1998) then changes to the tidal prism and sediment accreted or scoured from the intertidal banks are mutually exclusive (Kidd et al., 2016a). Tidal prism volumes are cumulative in the downstream direction, so a signal from that change should generally be detectable as bathymetric change at any point downstream.

FORM estimates a final equilibrium position following any combination of tidal prism changes in a coastal-plain estuary (Kidd et al., 2016a) (in a qualitative sense the concepts of FORM also apply to rias). FORM is a model based on a regime approach similar to that developed by Dennis et al. (2000) and others (Pethick et al., 2009; Spearman et al., 1996, 1998). FORM allows for incremental migration of the bathymetry through tidal prism variations due to tributaries, storages, or changes within the estuary, making it suitable for estuaries with multiple branches, tributaries and intertidal flats. The model is summarised as follows. The tidal prism at length x from the head is calculated from the exponent n in the (baseline) width equation $y=ax^n+c$ (Hood, 2002; Prandle, 2009) and the tidal range at x (c is a constant added to allow for the width of the fluvial river). A site specific tidal range equation is developed as a function of x and the product of this equation with the baseline width equation gives a tidal cross sectional area at x. When integrated, the tidal prism as a function of x is obtained. This allows for additional volume of storages and tributaries to be included in the model as tidal prisms are cumulative. The bathymetry effectively migrates either upstream or downstream depending on whether the tidal prism increases or decreases respectively (Fig. 5.1), as per the rule mentioned by Dennis et al. (2000). The migrated bathymetry will be scaled according to the synchronicity of the tidal waveform as the bathymetry is inherited from either a lesser or greater tidal range. Further, the anthropogenic adjustment may also affect the tidal range as with a barrage (Prandle and Rahman, 1980). Therefore, the migration is usually non-linear.

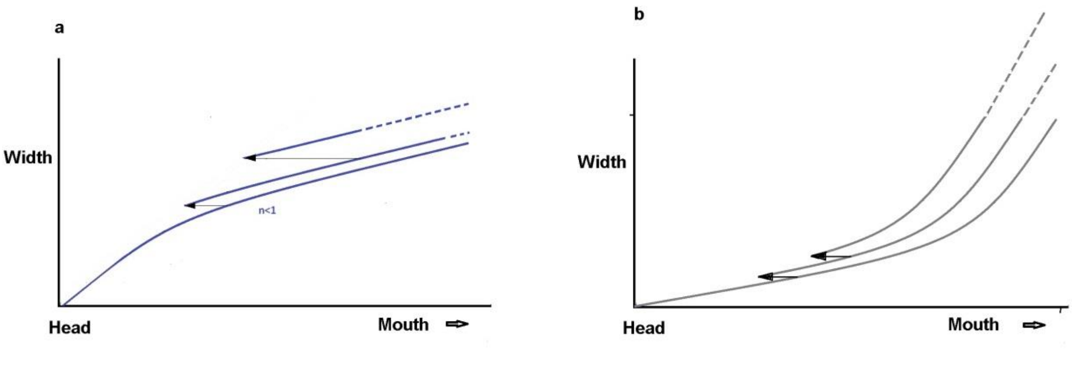


Fig. 5.1 The basis of FORM, (a) the effect of adding storages or tributaries to a bell-shaped estuary with n < 1. The lower curve is the baseline equation for the estuary without storages; and (b) the effect of adding storages or tributaries to a funnel-shaped estuary with n > 1 (e.g. upper Tamar, n = 1.78; Petitcodiac, n = 1.54 (Kidd et al.,

2016a)). Dotted lines are the extrapolation of the baseline width beyond the mouth. For loss of tidal volume, the direction of migration is reversed

The bathymetric migration caused by a TEB is obviously detrimental to the remnant estuary. We consider whether this trade-off is justifiable in terms of the positive mitigation against sea-level rise or whether other strategies such as increased accommodation space, fortification of existing defences, surge barriers or doing nothing, provide better alternatives. Our case-study sites are the Petitcodiac River in New Brunswick, Canada, the Avon River in Nova Scotia, Canada, La Rance estuary, France and the Tees River estuary, UK. The sites were chosen as each has some similarity with the Tamar River estuary, Tasmania Australia where various TEBs have been suggested as means of dealing with excessive siltation (Kidd et al., 2015). In the local printed and electronic media, La Rance, Tees and Marina (Singapore) barrages are cited by the proponents of a Tamar barrage whilst Petitcodiac, Avon and many others are cited by the detractors (Kidd et al., 2015).

1.2 The aim

Our analysis is in several parts. Firstly, we consider whether the morphological changes evident in our examples are consistent with the predictions of FORM. We also determine whether existing structures mitigate SLR (and what is protected) and would they have been built given the morphological outcomes. In light of these results, we consider whether an installation of a TEB in the Tamar River is justifiable. We hypothesise that the existing structures provide differing levels of protection and that none provide justification for a TEB in the Tamar River estuary.

2. Methods

2.1 Site descriptions

The location of each test site is shown at Fig. 5.2.

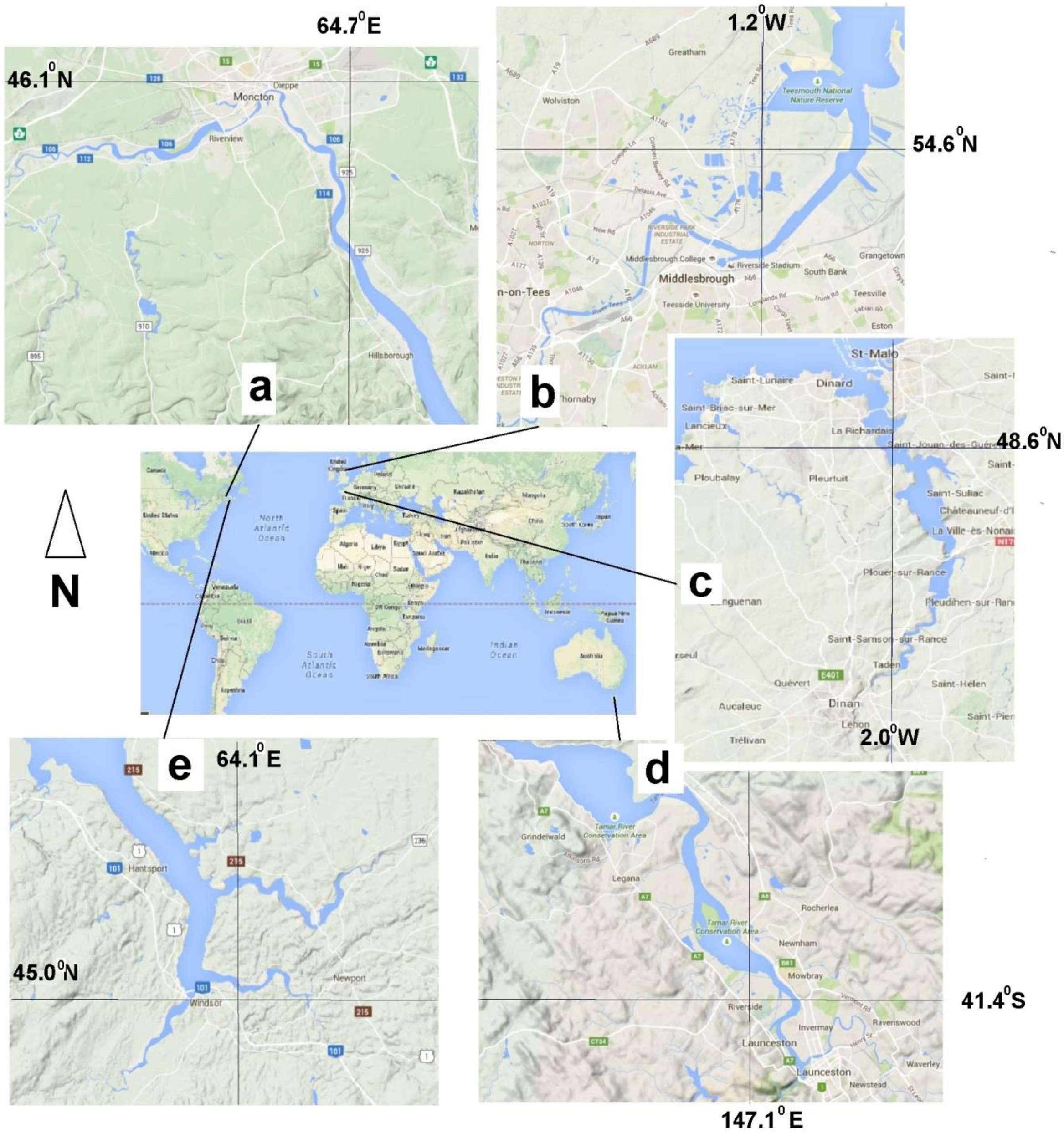


Fig. 5.2 Locations of the test sites; (a) the Petitcodiac River (New Brunswick); (b) the River Tees (UK); (c) La Rance (France); (d) Tamar River (Tasmania) and (e) Avon River (Nova Scotia)

2.1.1 Petitcodiac River

The Petitcodiac River Estuary (Fig. 5.2a) on the Bay of Fundy, New Brunswick, has one of the highest tidal ranges in the world of 16.3 m at Shepody Bay. Tides are semi-diurnal, suspended sediment concentrations are high (up to 2,835 $mg.l^{-1}$) and ice is present in the colder months (Van Proosdij et al., 2009). Riverine input to the system is relatively low at ~15 m^3sec^{-1}, making the Petitcodiac River estuary a hypo-tidal, well-mixed system. A tidal bore is present, which once had a height of 1-1.5 m but this reduced considerably when a causeway or TEB was built across the estuary in 1968 at Moncton. Before completion of the causeway, the estuary extended to Salisbury, ~15 km upstream. Post completion, the remnant estuary atrophied by up to 90% close to the barrage with the effect diminishing towards the mouth. Beaches formed upstream of the causeway aided by a net upstream transport of sediment through the fishway (Bray et al., 1982). The bathymetry below the barrage shows considerable temporal variation (Morand and Haralampides, 2006). Atrophied sections have been colonised by *Spartina alterniflora* which stabilized the deposits on the former intertidal areas. At 21 km downstream of the barrage, the cross sectional area decreased by 54% and at the mouth, the decrease was 18% due to a 3-5 m increase in the bed elevation (Van Proosdij et al., 2009). The barrage was partly opened in 2010, reinstating the tidal bore and partially restoring the tidal prism at the barrage. From the mouth to ~15 kilometres upstream, the estuary is typical of a ria, confined by rising ground. Further upstream the estuary becomes a coastal-plain estuary and is classically funnel shaped.

2.1.2 Avon River

The Avon River estuary in Nova Scotia (Fig. 5.2e) drains to the Minas Basin and then to the Bay of Fundy (as does the Petitcodiac). In 1970 the Avon was barraged at Windsor, ~1 km upstream of the confluence with the St Croix River. Downstream of the causeway, silt rapidly accreted to a depth of 6 m which was subsequently colonized by *Spartina alterniflora.* At the confluence with the Kennetcook River, accretion is less evident although Amos (1977) claimed an 8% reduction in cross-sectional area. The seasonal variation is high and Van Proosdij et al. (2009) dispute the 8%, suggesting it is well within the seasonal variation. They further claim that no significant decrease of tidal prism was measured pre to post causeway construction. The grade between the St Croix and Kennetcook Rivers decreased from 0.11% to 0.02% from 1958 to 2005 indicating an elevation of the bed, and a possible signal from the barrage.

Elevations indicated by Google Earth imagery show the (remnant) Avon River estuary bounded by rising ground with little intertidal, indicating that the estuarine type lies between a coastal-plain estuary and a ria. Pre barrage, the upper reaches were bell shaped and this shape is consistent to the mouth.

2.1.3 River Tees

In order to understand the bathymetric influences on the Tees (Fig. 5.2b) it is necessary to understand the historical context. Fig. 5.3 is compiled from a chronology of old maps dating from the early 1600s and show considerable evolution over hundreds of years. Middlesbrough for instance was once on the coast but due to evolution of the coast line is now ~10 km inland. According to Eisma (2005) the estuary was historically shallow and meandering and ~ 2000 ha of intertidal flats have been lost to dredge spoil and levees. The lower estuary was once a typical coastal-plain estuary meandering through erodible sediments but has since been straightened between Stockton-on-Tees and Middlesbrough, where two cuts, known as the Mandale Cut (1810) and the Portrack Cut (1831) were made to remove two meanders (Fig. 5.3), effectively shortening the estuary by ~ 5 km. The Tees barrage was built in 1995 close to the site of the Mandale Cut, but there is little trace of the former meanders. The pre-barrage estuary is shown by Lewis and Lewis (1983) as having a constant tidal range over its length but with a depth affected by extensive dredging. Since the cuts were made the channel has been made narrower in the belief that increased water velocity will increase scouring. Shoals and sandbars up to 300 m wide have been removed so that widths are now 100 m to 200 m. The net effect is to reduce the tidal prism downstream and lower the equilibrium position (Eisma, 2005). The estuary is now effectively a tidal canal and is constantly dredged, which hides the true impact of the barrage and loss of meander length. The old upper estuary was confined by both areas of rising ground and tidal levees, the latter removing all intertidal storages.

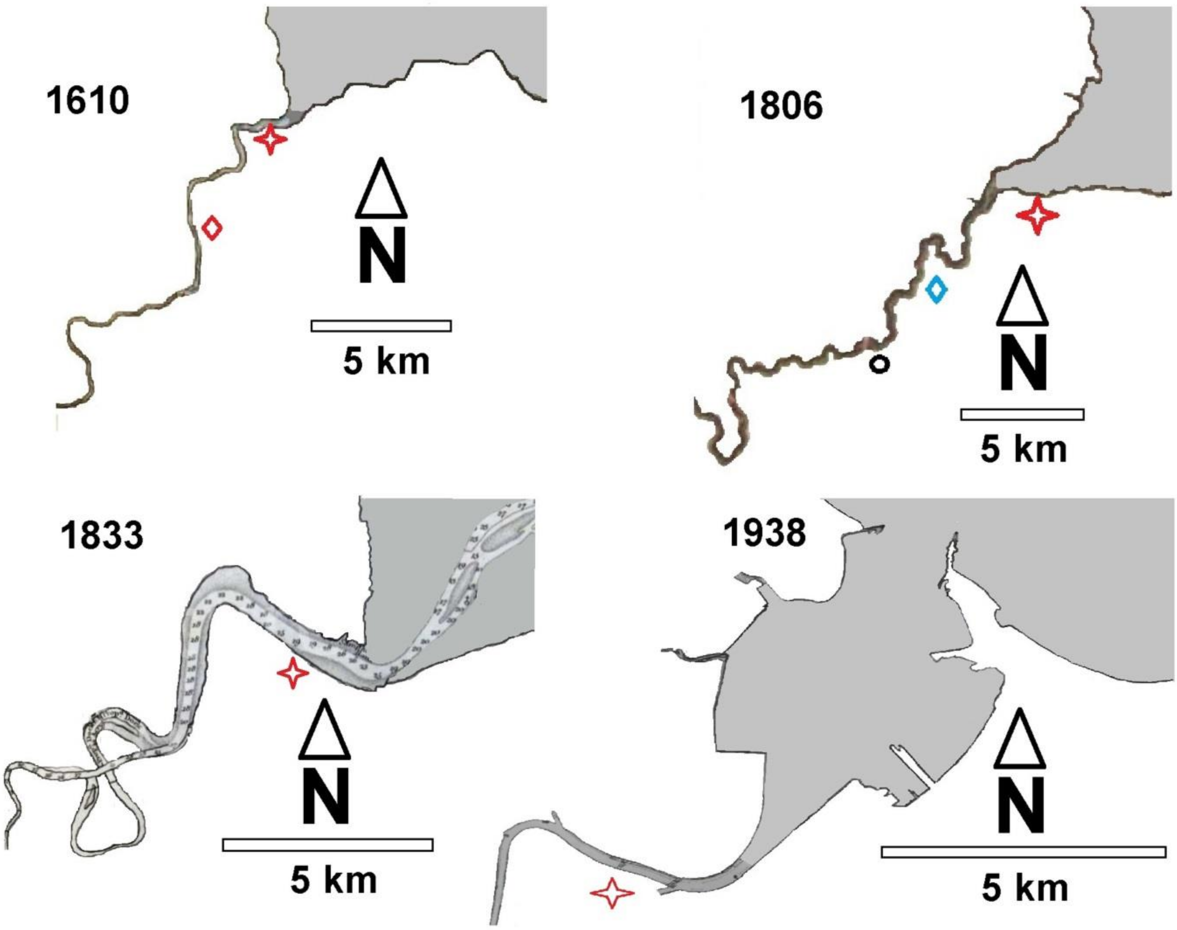


Fig. 5.3 Evolution of the River Tees since 1610. Middlesbrough (as denoted by the star) was once on the coast but is now 9.8 km from the mouth of the River Tees (Genmaps, 2015); scales are approximate

Prior to the building of the barrage in 1995, the tidal limit extended to Low Moor, which is 16 km upstream of the barrage. The impoundment water level is now constant (2.65 m ± 0.15 m above ordnance datum (AOD)) for 20 km upstream of the barrage (Lamping, 2003) which is approximately the pre-barrage mean high water spring tide (2.7 m AOD). The highest astronomical tide is 3.3 m AOD (JBA_Consulting, 2010) and the tidal range is 3.35m (mesotidal). Downstream of the barrage, the River Tees is vulnerable to high sea levels which result from a combination of high tides, storm surge, wave action and fluvial flows. The barrage has decreased the tidal volume at the mouth by 10% and reduced current velocities by a similar amount (Donoghue et al., 2004). The Emphasys Consortium (2000) report shows the cross-sectional area at the mouth of the Tees is considerably below equilibrium, which is almost certainly due to the training walls. It is likely that regime is established upstream, while dredged areas are above equilibrium (Eisma, 2005).

The Tees River barrage effectively protects ~ 16 km of the old upper estuary from the effects of SLR whilst the downstream section remains vulnerable. This area is newly in-filled, low-lying old intertidal and contains the port facilities and much of the industrial infrastructure of the region.

2.1.4 La Rance

La Rance estuarine system in Brittany (Fig. 5.2c) is hypertidal with a mean tidal range at St Malo of ~ 8 m (maximum ~ 13.5 m), where the permeable La Rance barrage and worlds first tidal power station was built in 1966. The lower estuary is confined by rising ground in the manner of a ria (Bonnot-Courtois et al., 2002) whereas 5 km upstream the bathymetry is that of a coastal-plain estuary with extensive intertidal flats. The maritime basin once stretched about 20 km beyond Le Châtelier lock (a TEB) which was commissioned in 1832 at Saint Samson sur Rance, ~ 12 km upstream of the St Malo barrage. Further upstream the old estuary, now a headpond, shows considerable variation in width due to old intertidal flats, despite being confined by rising ground (Fig. 5.4). This suggests an estuarine type between a ria and coastal-plain.

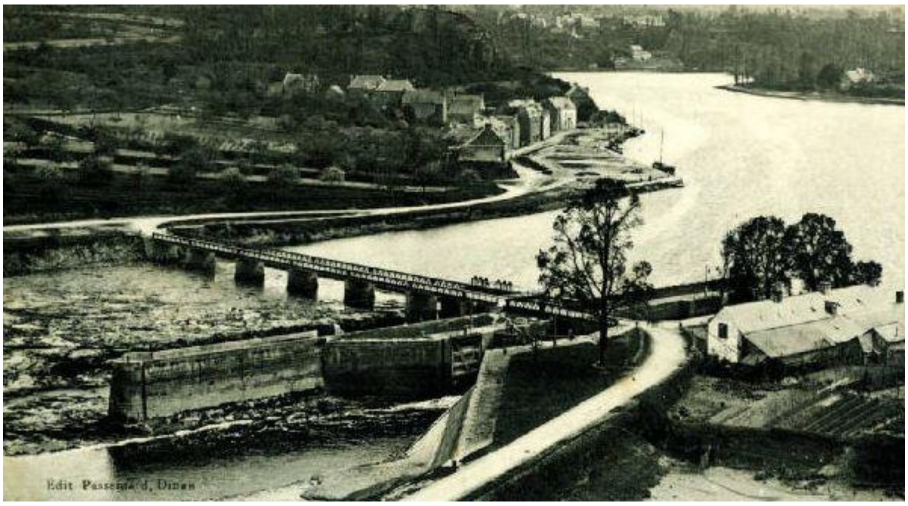


Fig. 5.4 Le Châtelier barrage and lock. (a) 1909 showing the natural rock ledge on which it was built and rising ground upstream confining the bathymetry and (b) view looking downstream from the barrage (2015) showing sediment built up below the barrage and sediment being flushed from the lock causing the turbid plume (centre left)

In 1966, impact assessments and procedures had not been refined to their present extent and did not exist in 1832 (Hooper and Austen, 2013). Neither barrage was built with any regard or knowledge as to their impact on the environment (Hooper and Austen, 2013; Pethick et al., 2009), which transpired to be significant (Le CRDP de Bretagne, 2014). The construction of La Rance barrage using two coffer dams and the subsequent operating regime caused significant mortality of marine species, as the intertidal area reduced from 70% to 50% of the total basin area (Hooper and Austen, 2013). This gives an indication of the effect of Le Châtelier barrage as the development of 70% intertidal in an estuary, generally considered to be a ria, is a significant accretion (although the initial area is unknown). Fine estuarine silt continues to be deposited between the two barrages and is frequently dredged to maintain navigable channels. The material comprises clay, silt and sand with high organic content (Jauberthie et al., 2010). Fluvial and marine sediment concentrations are low implying that morphological change from tidal prism adjustments will be relatively slow and regime equilibrium may take decades (Emphasys Consortium, 2000), although ecosystem recovery took just 10 years (Hooper and Austen, 2013; Retiere, 1994). The hydrological interaction between the two barrages and the ongoing dredging will complicate the understanding of the resultant morphological adjustment. Operation of the lower barrage has resulted in a 2.5 m rise in the mean water level (Hooper and Austen, 2013) as slack water periods are longer due to the retention of water post high tide. The tidal range has reduced by 40% (Kirby and Retiere, 2009; TETHYS, 2012). Less sea water enters the estuary due to the operation of the lower tidal power barrage and also therefore, less marine sediments (de Laleu, 2009). An alteration of the operating regime in June 1983 from ebb-only to two-way, exposed previously submerged mudflats and irregular operating periods from unexpectedly high tides and prolonged low water stands are now a feature (Hooper and Austen, 2013). Arguably the tidal power barrage effectively protects the upstream La Rance estuary from the effects of SLR.

2.1.5 Upper Tamar River

The Tamar River estuary (Fig. 5.2d) is ~ 80 km in length, and mesotidal. The upper 30 km comprises a silt belt with a distinct funnel-shaped bathymetry typical of a coastal-plain estuary. Closer to the coast the estuary is confined by a horst and graben structure typical of a drowned river valley or ria. The upper estuary consists of the main channel, two substantial tributaries and two large intertidal storages. Large areas of intertidal flats have been lost from the upper estuary due to canalisation and realignment (Davis and Kidd, 2012) and diversion of river flows in 1955 through a hydroelectric power station created a new tributary, known locally as the Tailrace. These changes have caused a build-up of sediment in the upper reaches around the city of Launceston and TEBs of various types have been suggested as possible solutions. Interestingly, SLR is not used as justification for a TEB and urban development is encouraged on the old intertidal flats (now protected by levees) with little regard to the threat of SLR (pers. obs.).

2.2 Approach

We used Google Earth to determine width of the high water mark against distance from the tidal extremity to the mouth of each estuary. Tidal extremity was assumed as that point where riverine width began to expand from former ~ constant width. We developed parameters *a*, *n* and *c* for the equation $w = ax^n + c$ for each estuary where *w* is the breadth, *a* is a site specific constant, x is the distance from the head, and c is the width of the fluvial river. A similar relationship exists for the depth $d = bx^m + c_2$. We developed headpond and remnant estuary width equations for four barraged estuaries, namely Petitcodiac (New Brunswick), Avon (Nova Scotia) the Tees (UK), and La Rance (France). Morris (2013) found erosion a common feature in headponds but we assumed that the present surface is an accurate representation of the former high water springs level. FORM was applied to the Petitcodiac, the Avon and the Tees but a paucity of data (and the fact that it is a ria) precluded its application to La Rance estuary. For the Avon River estuary, we estimated the volume of intertidal storages and tributaries and added them to the model as point sources, as per FORM (Fig. 5.1). The width equations allowed for a graphical representation of the effect of each barrage. This dataset was used to calculate the coefficient of determination R^2 between the modelled and sampled widths. Where appropriate we have used linear regression between before and after widths (i.e. the width of the headpond against the width of the remnant estuary).

For the case of the relatively simple Petitcodiac River, we used Google Earth imagery from 2004, prior to the partial re-opening of the barrage in 2010. The before and after width-plots demonstrate the bathymetric migration due to the barrage and are sufficient to validate FORM in this instance. The Avon River estuary is influenced by three major tributaries and the application of FORM is required to model their combined effect on the bathymetry.

For the Tees, we measured the present headpond and remnant estuary widths every 100 m for 14 km and 16 km respectively. We developed a width equation for the remnant estuary from widths measured on Google Earth from imagery of 25th July 2008. In the case of La Rance, FORM does not apply as the system is a ria. However we firstly discuss the effects of the upper barrage (Le Châtelier) using the underlying principles of FORM assuming that a new regime equilibrium had been attained by 1966. Secondly, we discuss the effects of the lower barrage; that is a reduced tidal range and an increase in mean sea level. Again, FORM is not applicable as it can only predict downstream effects of such changes.

The morphological impacts of TEB installation in the Tamar River were modelled using FORM by Kidd et al. (2015). They found that the potential impacts did not justify the installation of a TEB. We reassess that conclusion in light of potential mitigation of SLR and the inferences gained from the above case-studies.

3. Results

The characteristics of each estuary vary and summary and relevant results are at Table 5.1.

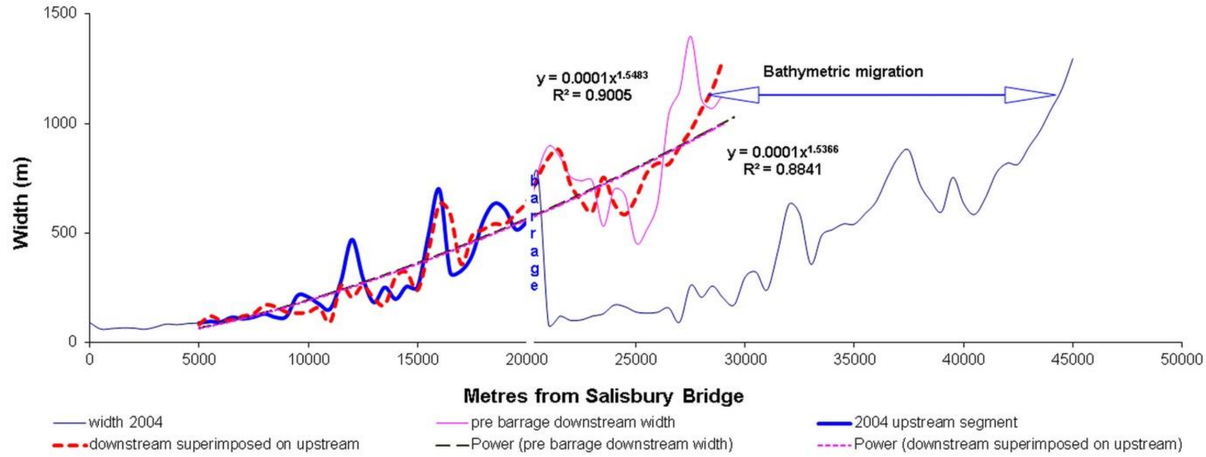
Table 5.1 A summary of characteristics for each test site

	Upper Tamar (Tasmania)	**Petitcodiac (New Brunswick)**	**Avon (Nova Scotia)**	**Tees (UK)**	**La Rance (France)**
Estuarine type	Coastal Plain	Coastal Plain-Ria	Coastal Plain	Coastal Plain	Ria-Coastal Plain-Ria
Tidal range (m)	2.34-3.25*	>15m**	9.26**	3.37**	6.83**
Classification* **	Mesotidal	Hypertidal	Hypertidal	Mesotidal	Hypertidal
Tidal regime	Hyper-synchronous	Hypo-synchronous	Hypo-synchronous	Synchronous	Synchronous
Width exponent	1.74	1.54 (C-P); <1 (Ria)	0.8	2.05	1.78
Depth exponent	0.5	Data unavailable	Data unavailable	1.0	Data unavailable
Shape factor	1.86	Data unavailable	Data unavailable	3.05	Data unavailable
Stressors	Levees, Freshwater flow regime, silt raking	Barrage	Barrage	Barrage, levees, meander removal, dredging	1x Permeable barrage, 1xTotal exclusion barrage, dredging
Bathymetric migration evident	Confirmed by FORM	clearly	Visually evident for 2km; confirmed by FORM	Hidden by other anthropogenic adjustments	Pre 1966 Contraction post 1966

*(Kidd et al., 2016a)** (Meteo365, 2016), ***(Dyer, 1997)

3.1 Petitcodiac River estuary

The barrage on the Petitcodiac River has clearly produced a migration of the channel bathymetry from upstream to downstream of the barrage (Fig. 5.5). Intertidal storages also show an unexpected migration which FORM is unable to predict. Figure 5.4 shows almost identical trend lines above and below the barrage and a slight compression of the length in the remnant estuary (*n* increased from 1.5366 to 1.5483 or 0.7%) which is indicative of a slight increase in the tidal range, hypo-synchronicity, or both. The trend-line slope from the linear regression analysis was 0.95 with y intercept forced to zero and 0.85 with y intercept of 14.9 m. The value of *n* for the system, including intertidal storages, is consistent with a funnel-shaped estuary. We found the trendline coefficient (0.0001) too small to account for a width at the mouth (confluence with the Memramcook River) of ~1400 m for the barraged scenario, and that a coefficient of 0.00012 was required as a minimum. The migratory effect is discernible through the ria section as the depth at the mouth has reduced by 3-5 m (Van Proosdij et al., 2009) although little variation in width is evident. The TEB which existed from 1978 to 2010 effectively protected ~16 km of estuary from the effects of SLR.



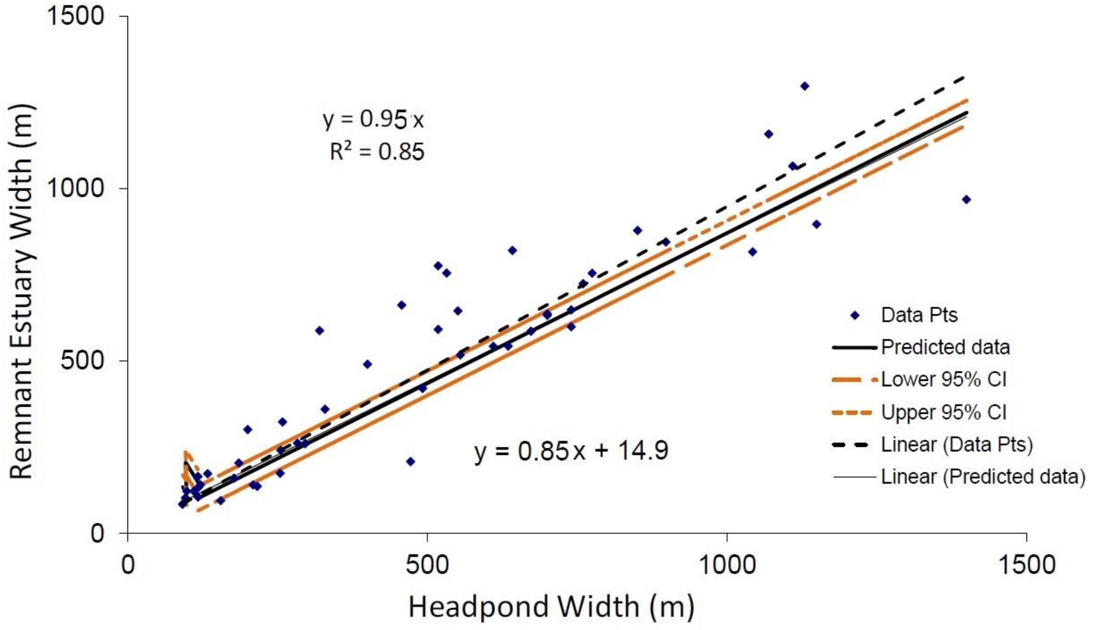


Fig. 5.5 The effect of the Moncton Barrage on the Petitcodiac River estuary. (a) Showing a clear migration of the bathymetry and close correlation of the trend lines for post and pre barrage bathymetries and (b) the linear regression showing 95% confidence intervals

Forcing the y intercept to zero in the linear regression shows ~1:1 relationship for the variables. The y intercept of 14.9 and slope ≠1 shows that the old tidal limit was further upstream than the position used in the analysis.

3.2 Avon River estuary

Graphical analysis (Fig. 5.6) shows n ~ 0.8 for the old upper Avon River, consistent with a bell-shaped estuary. Post barrage, bathymetric migration is evident for just 2 km due to the confluence of the St Croix River and the large tidal prism which it contributes to the system. However with FORM applied, the migration is evident over the length of the estuary (Figure 5.5b). A correlation $R^2 = 0.96$, $p < 0.001$ was found between the old bathymetry and that of the predictions of FORM. FORM predicted a 12% reduction in the width at the mouth of the system due to the barrage, but with $n = 0.81$ (an increase of 1. 25%) the width at the mouth was unchanged ($R^2 = 0.94$). FORM also shows that the width at the St Croix confluence is beyond equilibrium and that additional accretion can be expected. The underlying (compressed) bathymetric migration of the Avon is best illustrated in Fig. 5.6, although amplification of the width may be due to an increase in the tidal range. As an order of magnitude calculation, we estimated the total surface area of the Avon system to be ~$41*10^6$ m^2 and the area of the Upper Avon to be ~$2.8*10^6$ m^2. Assuming a tidal range of 9 m throughout then the tidal volume at the mouth is ~$370*10^6$ m^3. A linear regression analysis is not appropriate for the Avon as the underlying migration is effectively masked by the proximity of the St Croix River to the barrage.

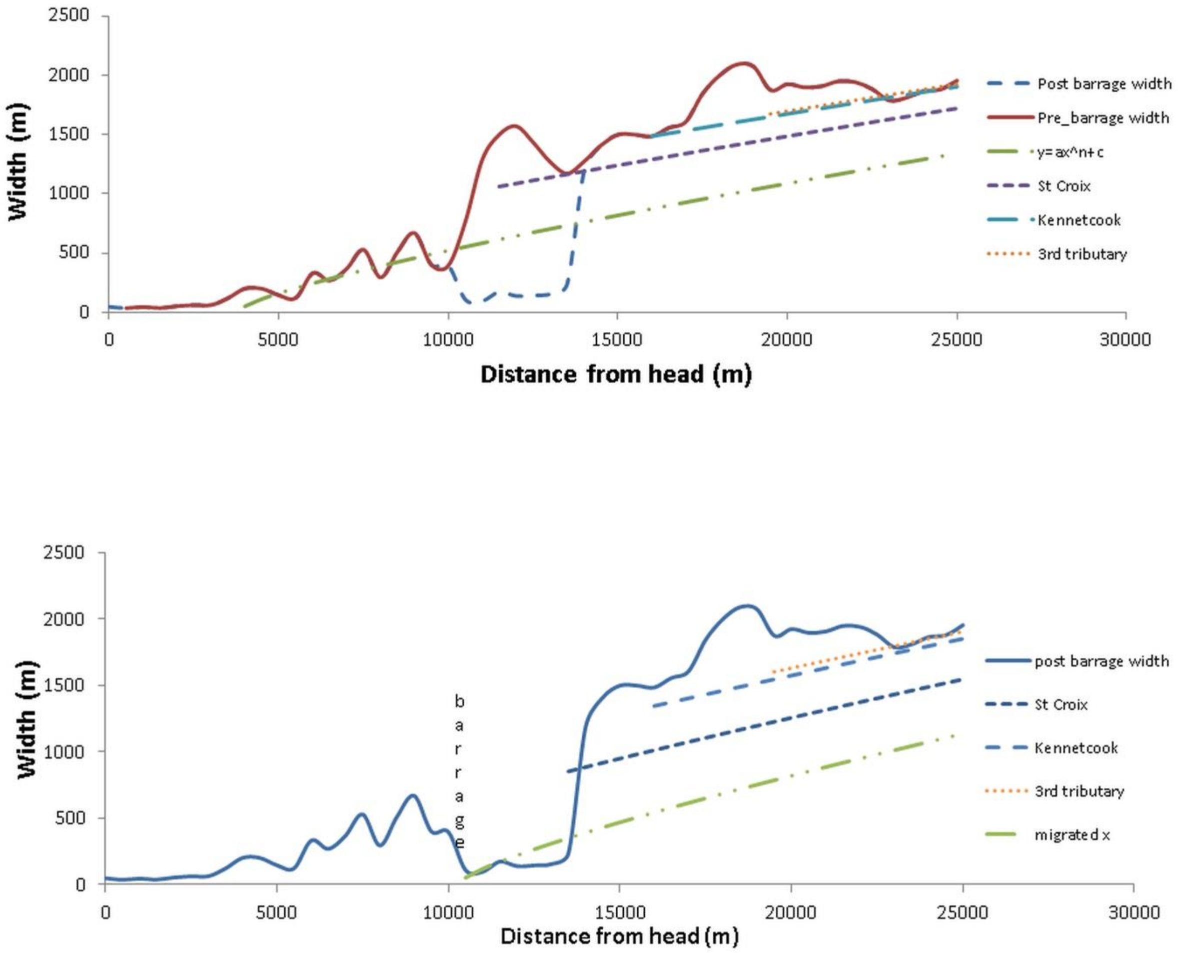


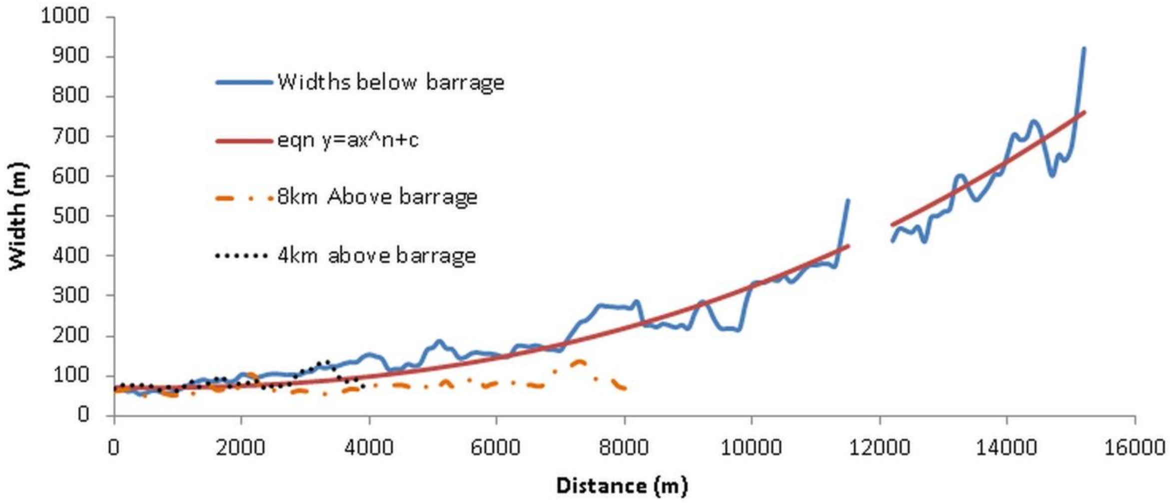
Fig. 5.6 FORM applied to the Avon River estuary; (a) pre barrage and (b) FORM applied to post barrage estuary. The effect of each tributary is shown extrapolated to the mouth. Data sourced from Google Earth

The baseline bathymetry attributable to the Avon has migrated ~7 km due to the barrage at 10500 m and *n* is increased from 0.8 to 0.81 commensurate with a small increase in tidal range.

3.3 River Tees estuary

The highly modified nature of the Tees River estuary complicates the calculation of the historical values for *n* (Table 1). The remnant estuary equation parameters were derived as $a = 0.77*10^{-7}$, $n = 2.38$ *and* $c = 70$ ($R^2 = 0.9598$, $p < 0.001$) (Fig. 5.7). Although the past tidal distance was 16 km (Lamping, 2003), we found a correlation of the remnant estuary with the headpond ($R^2 = 0.42$) for ~3.5 km indicating an incomplete migration.

The mouth is constricted by training walls and was under equilibrium before the barrage was installed (Emphasys Consortium, 2000) despite extensive dredging of the mouth. Our results show that post barrage the regime width for the mouth is ~750 m, assuming a full migration of the bathymetry. The channel inside the mouth adjacent to the (un-dredged) broad expanse of Seal Sands will have also received a signal from the barrage and hence accretion can be expected there.



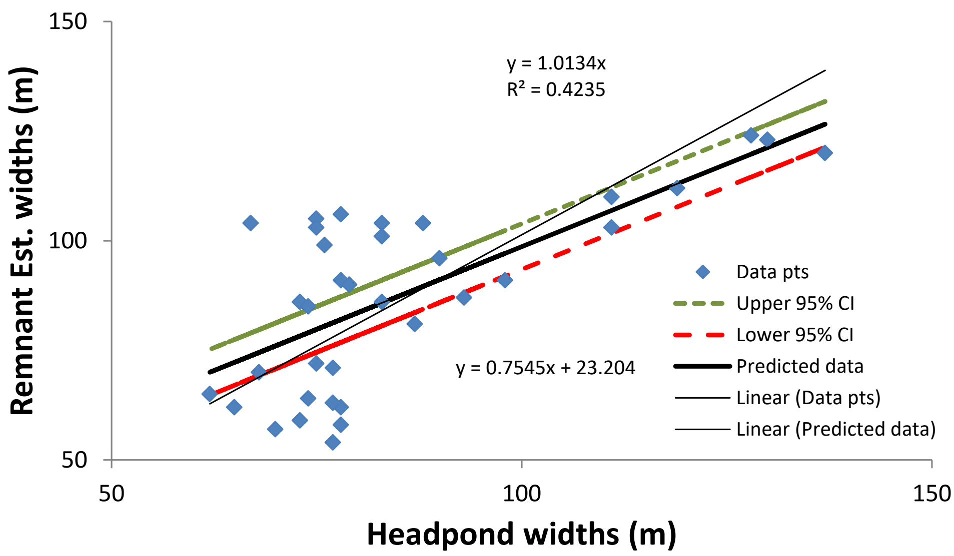


Fig. 5.7 Bathymetric migration of the River Tees. (a) The width of the remnant estuary superimposed over 4 km and 8 km of headpond upstream of the barrage showing a possible bathymetric migration of ≤ 4 km in the River Tees and (b), the linear regression plot for a 3.5 km migration showing 95% confidence intervals

With the y intercept forced to zero (Fig. 7(b)) the relationship is ~1:1, but R^2 value is low. The y intercept for the predicted values is 23.2 which is likely due to the canalisation of the old upstream estuary.

3.4 La Rance estuary

Three distinct bathymetric widths are evident on Google Earth imagery; the 1830s high water level, the present high water level and the present low water level. We calculated the corresponding width equations as; $y = 1.7*10^{-5}x^{1.91}+10$ (R^2 = 0.85, p < 0.001), $y = 5.2*10^{-7}x^{2.4} + 21$ (R^2 = 0.97, p < 0.001) and $y = 1.2*10^{-7}x^{2.4}+17.8$ (R^2 = 0.96, p < 0.001). The precise geometry of 1966 is not known, but post 1966 the mean sea level in the remnant estuary has risen by 2.5 m and the tidal range has decreased by 40% (Hooper and Austen, 2013). FORM does not apply in this instance as La Rance estuary is a ria and the above equations are used for qualitative purpose only. The lack of historical bathymetrical data precluded an analysis of the individual effects of each barrage. However, the combined effects show a bathymetric migration, albeit a distorted one (Fig. 5.8).

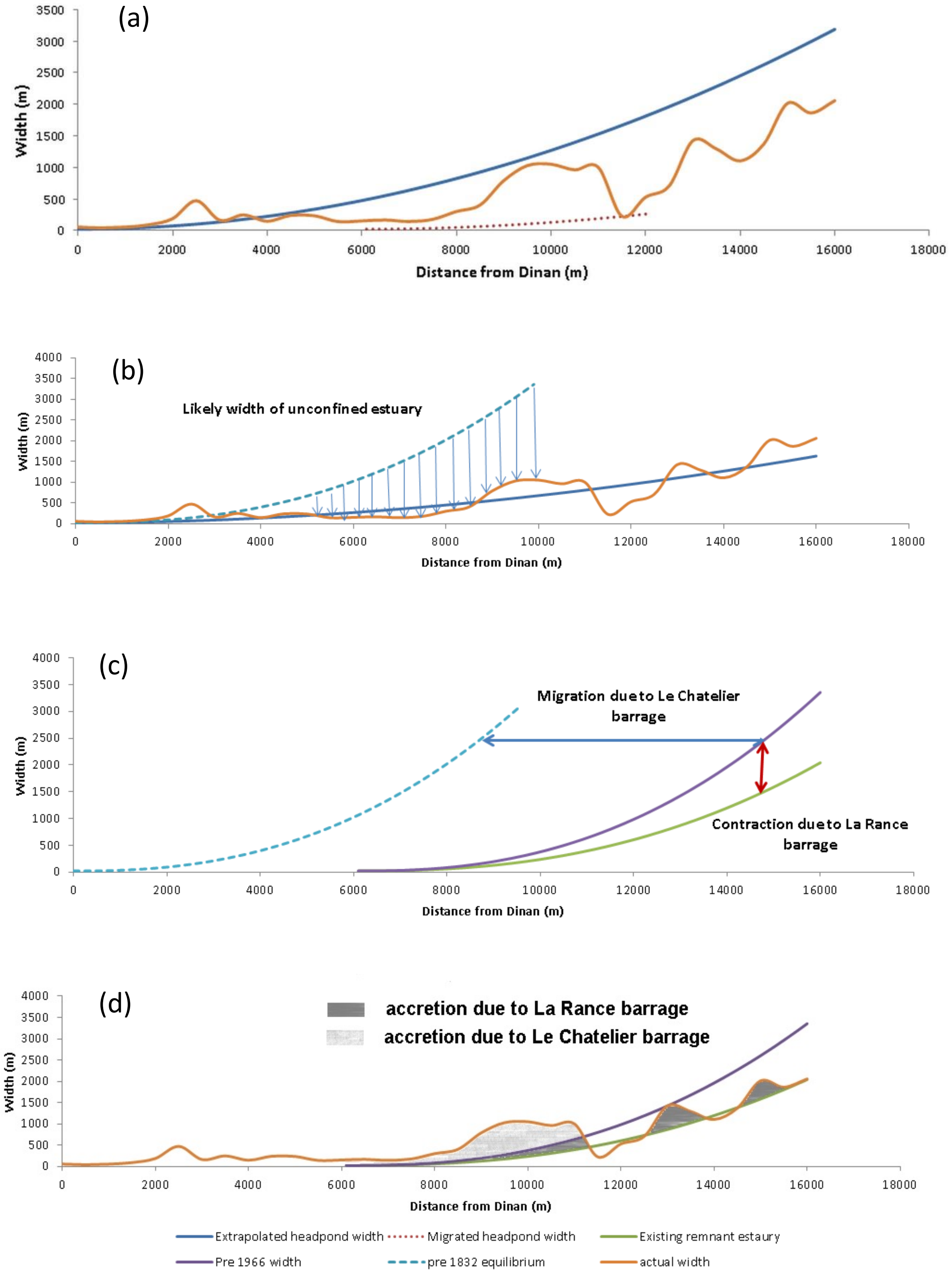


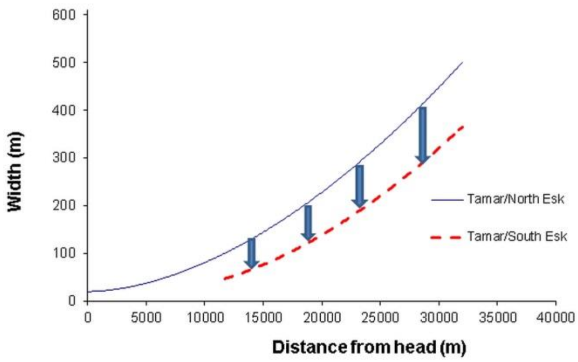
Fig. 5.8 A qualitative assessment of the evolution of La Rance estuary due to Le Châtelier and La Rance barrages. (a) Original width and trendline, and migrated

headpond trendline. The migrated headpond width is no longer confined by the rising ground of the ria; (b) likely width of unconfined estuary (note old intertidal area at ~2000-3000 m); (c) evolution of trendlines with original removed for clarity and (d) evolution of intertidal areas due to each barrage

3.5 The upper Tamar River estuary

FORM is restricted to the upper section of the Tamar which is typical of a coastal-plain estuary. Two separate barrages are modelled, one across the mouth of the North Esk River (Fig. 5.9.a) and another at Stephenson’s Bend which incorporates re-routing the North Esk River to downstream of the barrage (known locally as the Lake Batman Project) (Fig. 5.9b)

(a)



(b)

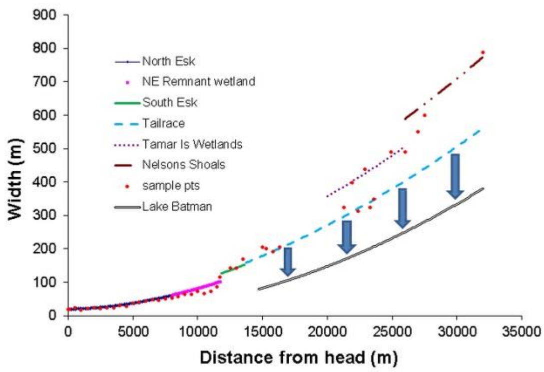


Fig. 5.9 FORM results for barrages in the upper Tamar River estuary; (a) a barrage at the mouth of the North Esk River and (b) the effect of the Lake Batman barrage

For both the modelled barrages, the width at the barrage is approximately halved and the contraction increases slightly over the downstream silt belt, indicating a significant accretion. For those barrages closer to the coast in the ria section of the estuary, Le Châtelier is a suitable analogue, and the prognosis is equally detrimental.

4. Discussion

As predicted by FORM, our results confirm that bathymetric migration due to anthropogenic influences on the tidal prism is evident at each of our test sites. Each TEB protects a relatively small area from the effects of SLR whilst the adverse morphological change in the remnant estuaries varies from minor to severe. None of the four test cases provide supporting evidence for the use of a TEB for SLR mitigation in the Tamar River estuary. Other than for the Petitcodiac, bathymetric migration, and hence downstream degradation due to sedimentation, is not always obvious. For example, the barrage in the River Tees estuary in the UK appears to have little effect on the bathymetry due to dredging, canalisation and constriction of the mouth, but perhaps manifests as accretion inside the mouth (at Seal Sands).

The modelling of a TEB installation is a simple application of FORM. The TEB removes 100% of the tidal prism at the point of installation and FORM assumes that the bathymetry from the head of the estuary (now a headpond) will reform from that point (Fig. 5.10). Again, the synchronicity of the estuary and other tidal range effects are important and will affect the final geometry. Prandle and Rahman (1980) developed a shape number for estuaries, $v=(n+1)/(2-m)$, where depths are proportional to x^m and breadths x^n and showed how this number applied to differing estuary types from ria to coastal-plain to bar-built. The shape number helps in understanding the tidal amplification and the type of estuary. In particular it identifies coastal-plain estuaries for which FORM is best suited, but the width exponent (*n*) is the most convenient indicator of the resultant bathymetry should a change occur as on site sampling is not required. Coastal-plain estuaries are not necessarily all funnel shaped and adjustments will differ. For instance, an estuary with the width exponent $n < 1$ is bell-shaped and will show less impact at the mouth (or at any section downstream) for a reduced tidal prism than will a funnel-shaped estuary with width exponent $n > 1$ (Fig. 5.10a). Hood (2002) showed an exponent of 0.88 for tidal sloughs, whilst the exponent for the upper Tamar River estuary is 1.78 (Kidd et al., 2016a), indicating that the downstream signal from any anthropogenic change may be more pronounced than if $n < 1$. The final configuration will also be influenced by the synchronicity of the estuary and any changes to the tidal range. Hence, the bathymetric migration evident in the remnant estuary may be longitudinally scaled (non-linear) (Fig. 5.10(b), 5.10(c)).

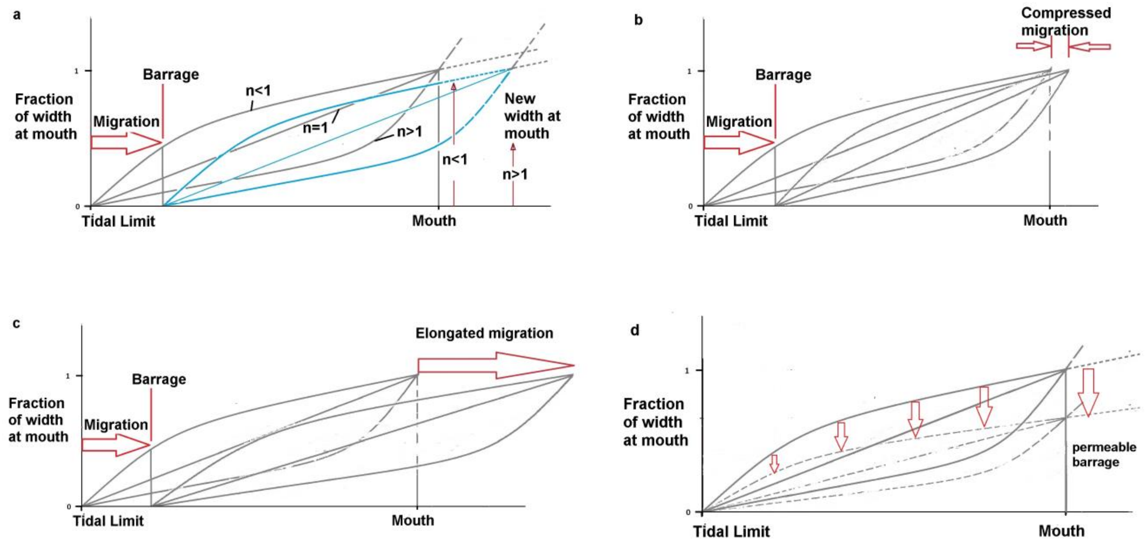


Fig. 5.10 Simple bathymetric migration due to a total exclusion barrage in synchronous estuaries of various shapes, assuming no change to the tidal range. (a) The signal from the barrage at any point downstream is greater for funnel shaped estuaries (n>1), (b) compressed migration for hypo-synchronous estuaries or where the tidal range has increased due to the modification, (c) elongated migration in hyper-synchronous estuaries or where tidal range has decreased due to the modification and (d) compression of the bathymetry due to a permeable barrage

4.1 The Moncton Barrage on the Petitcodiac River

The Petitcodiac River is the simplest of the test sites in that it is has little intertidal storage and no substantial tributaries. The high sediment regime means that the full impact of the barrage installed in 1968 is evident as regime has been attained relatively quickly (Van Proosdij et al., 2009). The application of FORM is a transposition or migration of the channel bathymetry from the old head of the estuary to the barrage (Fig. 5.10.b) and this is clearly evident from the plot (Fig. 5.5(a)).

An upstream exponent $n > 1$ and $n < 1$ near the mouth, is consistent with a coastal-plain estuary morphing to a ria. Fig. 5.5(a) shows a clear migration of the bathymetry as hypothesised, but bathymetric migration is truncated somewhat short of the mouth due to $n < 1$ over the downstream section. For $n = 1.55$, and a coefficient of 0.00012, the width at the mouth ought to be ~ 2200 m for the un-barraged system (x = 52000 m) and ~ 1490 m for the barraged system (x = 36000 m). Therefore the confines of the ria (~ 1450 m wide) are sufficient to restrict the width of the barraged system and the signal from the barrage manifests as a reduction in depth and no change to the width.

Both the channel bathymetry and the size and positions of intertidal storages have migrated. The former validates the FORM model but the latter was unexpected, perhaps due to an underlying pattern in the substrata or a natural meandering frequency caused by the flow regime. The trade-off for protecting ~ 21 km of upper estuary from SLR has been the degradation of the remnant estuary to ~ 10% of the former width. The TEB was partly reopened in 2010 with the option for it to be closed in the event of tidal surge and it remains to be seen whether the remnant estuary will ever regain its former width.

Referring to the Moncton barrage, Suzuki and Moola (2010) commented “It's hard to imagine that people once thought blocking a river in such a way was a good idea. It's another example of how we humans often act without enough knowledge to fully understand what the consequences of our actions will be.” The partial removal of the barrage was instrumental in the Petitcodiac River being a finalist in the *Thiess International Riverprize* sponsored by the 17th International River Symposium in 2014 (International River Foundation, 2014). It is ironic that since opening of the barrage in 2010 the opportunity arises for its’ use as a tidal surge barrier, whilst allowing the estuary to return to its’ natural state. Effectively it provides better protection from SLR now that it is open than when it was closed. Putting the merits of the barrage to one side, the pre 2010 barrage provided an ideal test site and showed the applicability and benefits of using FORM.

4.2 The Windsor Barrage on the Avon River

The high sediment concentrations in the Avon have produced rapid morphological change similar to that present in the Petitcodiac River. With $n = 0.8$, the shape is similar to tidal sloughs (Hood, 2002); possibly due to low fluvial flow compared to tidal flow. Van Proosdij et al. (2009) claim no change of tidal prism post barrage, which implies there is no change in cross-sectional area at the mouth. This suggests that there must have been an increase in tidal range to compensate for the loss of tidal prism at, and seaward of, the barrage. FORM shows that, consistent with a tidal range increase, an increase of n from 0.8 to 0.81 is required to model the post barrage situation. Our order of magnitude calculation shows a tidal range increase of ~6% is required for no change of tidal prism at the mouth per Van Proosdij et al. (2009). The Windsor barrage was built to protect the tidal levees of the upper Avon River, and it is possible that the canalisation restricted the width of the old estuary so that the migrated width is somewhat wider than expected (this effect, as shown at Fig. 5.10(b), is observed in La Rance and is discussed in **4.4**).

The underlying bathymetric migration is evident for 2 km downstream of the barrage where the effect is nullified by the large tidal prism of the St Croix tributary. Silt accretion near the mouth of the St Croix River has effectively moved its' mouth ~ 1.5 km seaward.

Van Proosdij et al. (2009) suggested that the Windsor barrage in Canada is anomalous, and concluded that "(one can) not assume that all tidal barriers exert the same influence in every location, as little effect of the Windsor Barrage is discernible on the Avon River". In this instance, the Avon, which accounts for 24% of the watershed, is now effectively a tributary to the (now) larger St Croix and Kennetcook River systems. Further, Amos (1977) suggests that contraction of the cross-sectional area is ~ 8% in the reach between the St Croix and Kennetcook Rivers and ongoing progradation is present, notwithstanding that the bed elevation has high seasonal variability (up to 6 m). However, we have shown through the application of FORM (Fig. 5.6) that the present bathymetry was predictable. The effect of the Windsor Barrage is consistent with the effects of other TEBs, and just ~ 7 km of old estuary is protected from SLR. Whether the sacrifice of 2 km of remnant estuary to excessive siltation is a justifiable expense for the protection from SLR of ~ 7 km of upper estuary remains subjective.

4.3 The River Tees Barrage

The River Tees has undergone a dramatic evolution over the centuries. Many other estuaries in the UK (including The Ribble, Ouse, Eider, Blyth, Mersey, Humber, Breydon Water) have met a similar fate. In the 1600s the Tees flowed to a wide bay where a bar has since formed effectively lengthening the estuary by ~10 km (Fig. 5.4). For regime modelling purposes, this requires an extension of the old bathymetry with the then values of n and m, assuming that these have remained constant. The removal of the two meanders effectively shortens the estuary by 5 km and so the net increase can be assumed as ~ 5 km. Canalisation has removed intertidal storages and reduced the equilibrium of downstream sections.

There appears to be little discernible downstream impact due to the barrage. The intertidal known as Seal Sands continues to accrete and the question is whether this is attributable to the barrage. Undoubtedly the barrage has reduced the tidal prism but the bathymetric migration of ~ 3.5 km is not clearly defined (R^2 = 0.42, linear regression line slope = 1 for forced y intercept = 0). For the highly canalised estuary the underlying shape remains consistent with a coastal-plain estuary with n ~ 2.38 and m ~ 1.0.

The mouth is highly constricted according to Emphasys Consortium (2000). Their unnumbered figure in chapter 5 shows the equilibrium position well below other UK estuaries. However, the cross-sectional area (below mean tide level) is ~ 7000 m^2 which is above equilibrium, whereas equilibrium is ~ 3500 m^2 for a tidal prism ~ $30*10^6$ m^3. This is indicative of a width at the mouth confined by training walls and a depth increased by dredging. Modelling commissioned by English Nature (HR Wallingford, 1966) suggested that the Tees Barrage would have limited impact on sedimentation on Seal Sands although a further study by Donoghue et al. (2004) suggested that the intertidal zone within the lower Tees estuary is in a state of net accretion. The latter is consistent with our results.

The high river discharge of ~ 20 m^3sec^{-1} (Lamping, 2003) produces a reach of freshwater of low turbidity in front of the barrage, where an atrophied cross section would be the norm. However the barrage is so designed that the discharge is spread over the width of the structure, thus minimising this effect (c.f. the Petitcodiac where the discharge is more localised)

Being a synchronous estuary, little distortion of the migrated estuary can be expected although there may be some increase in the tidal range. This may be a contributing factor to the short migration distance (< 4 km). The ongoing evolution and accretion is almost certainly being driven by 700 000 tonnes of marine sediment entering the system annually (Donoghue et al., 2004; Eisma, 2005) compared to 40 000 tonnes of fluvial origin. The model of van Dongeren and de Vriend (1994) showed a barraged estuary accreting from the mouth driven by such marine sediment. Accretion inside the mouth is therefore predictable, whereas the estimated 40 000 tonnes pa of fluvial sediment is effectively trapped by the barrage.

As expected, evidence for bathymetric migration in the highly canalised and constantly dredged River Tees estuary is less obvious than for other systems, but we maintain that ongoing accretion at Seal Sands is indicative of its existence. Derivation of the width equation for the headpond was problematic due to canalisation in the upper estuary. It is evident from Google Earth imagery that large areas of old intertidal storage have been lost to tidal levees and canalisation has reduced the natural width of much of this section. Other sections are confined by rising ground resulting in a weak correlation (R^2 = 0.42) between remnant estuary equation and headpond width. Continued dredging lessens the visual impact of the barrage but is now required to maintain the present bathymetry or accretion, mostly of marine sediment, will occur (Eisma, 2005). The canalisation of the estuary was designed to increase flows and scouring but our results show that the bathymetry has migrated ~ 3.5 km as a consequence of the barrage.

When developing FORM in the upper Tamar River estuary (Kidd et al., 2016a) made the assumption that the intertidal storages migrated laterally in unison with the channel width and that the tidal volume over the flats remained roughly constant. This requires net accretion over the flats. Perhaps this is the effect observed at Seal Sands, as the channel width will have reduced due the barrage and subsequent reduction of tidal prism. Figure 5.4 shows a net accretion at Seal Sands for centuries and our results show no reason why this should not continue.

4.4 Le Châtelier barrage on La Rance estuary

Most studies of the La Rance focus on the lower barrage built in 1966 but our results show that Le Châtelier barrage built in 1832 also had a significant influence on the estuarine bathymetry. A migration has occurred from the confines of the upper estuary to the (now) less confined lower ria such that the latter has partly transformed into a coastal-plain estuary with extensive areas of intertidal. This effect is most noticeable in the 6 km fetch from Le Châtelier to the first constriction (due to the ria) at Le Port Saint-Hubert. A paucity of historical data on the La Rance means our results must be considered with due caution. Figure 5.4 clearly shows the expected accretion immediately downstream of the Le Châtelier barrage and lock which was installed 77 years previously. The width equation applicable to the present day bathymetry upstream of the lock, provides n = 1.91 indicative of a funnel shaped estuary. Although Figure 5.4 shows the old upper estuary confined by rising ground, there is evidence of an old intertidal area 4000 m downstream of Dinan and other areas of floodplain, indicating that in places, the rising ground did not significantly restrict the natural width of the old estuary. However, the headpond has now existed for 182 years and considerable evolution of the surface shape can be assumed (Morris, 2013).

The building of Le Châtelier barrage in 1832 will have adjusted the local tidal prism in the manner of all other TEBs. We can assume that by the time the La Rance barrage was built 134 years later, that La Rance had regained regime despite low levels of fluvial sediment input. Our only supporting evidence is Figure 5.4 and others like it. Pre 1966, downstream of Le Châtelier the remnant estuary had morphed from one confined by rising ground to one where intertidal flats comprised 70% of the area (Hooper and Austen, 2013), consistent with a coastal–plain estuary. The constriction at Le Port Saint Hubert provides a natural limit to the analysis. Figure 5.5 shows the accretion downstream of the barrage as expected, and the bathymetric migration is confirmed (Fig. 5.8) despite the later two-staged effects of La Rance tidal barrage. The lack of bathymetric data from pre 1966 means the morphological effect of La Rance barrage is not quantifiable. However Figure 5.8 shows this effect to be small in the upper remnant estuary despite changes to the tidal range (decreasing by 40%), raising of the mean water level (2.5 m) and lowering of the tidal prism (which should have raised and atrophied the channel (Fig. 5.11)). Perhaps this effect has been countered by the artificial retention of high and low water levels (de Laleu, 2009) and on-going dredging.

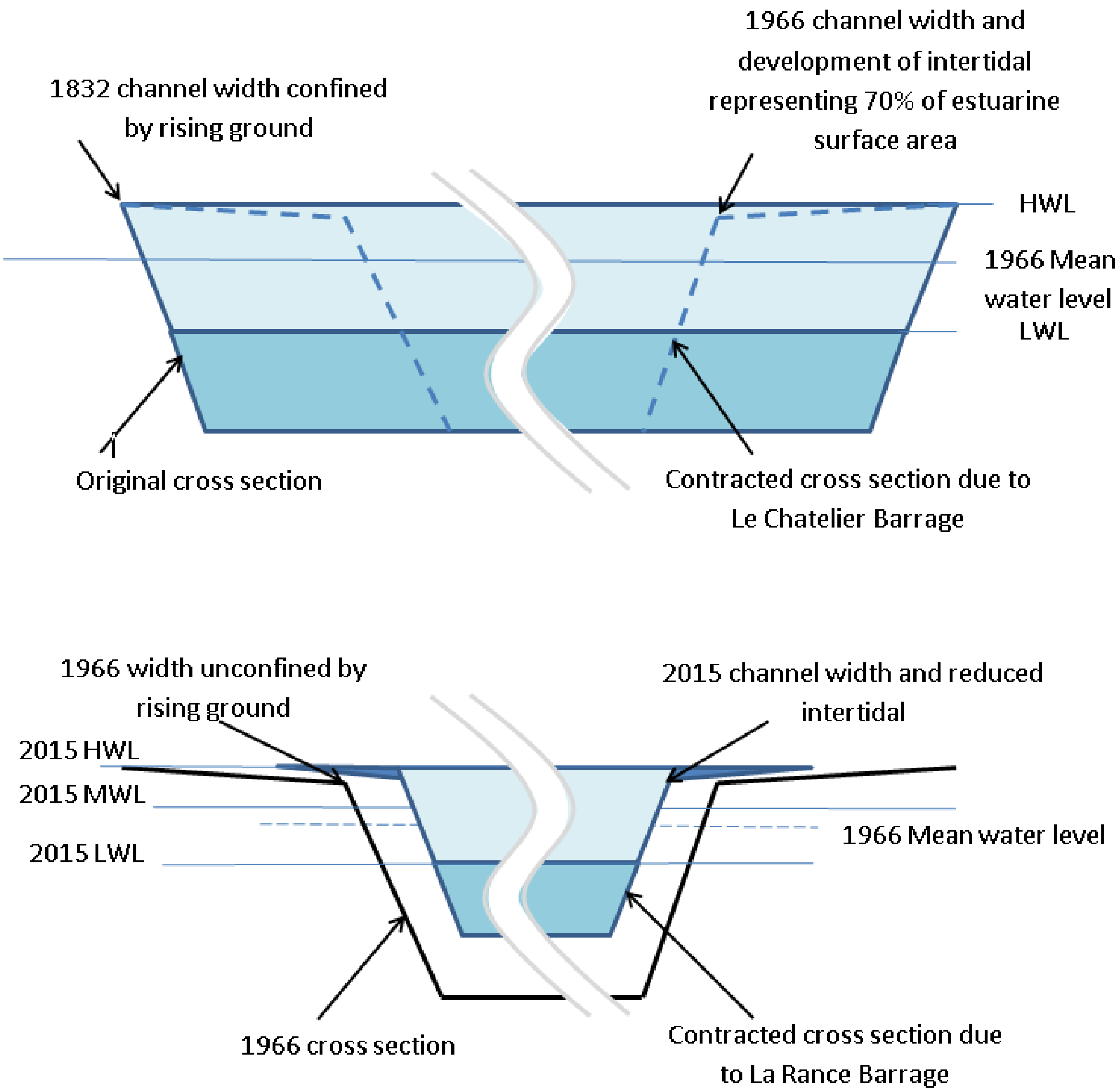


Fig. 5.11. Evolution of La Rance estuary due firstly to Le Châtelier Lock (barrage) and secondly to La Rance tidal power barrage

4.5 Upper Tamar River estuary

A full assessment of TEB installation in the Tamar River is given by Kidd et al. (2015), who concluded that the morphological implications of any barrage would be severe and that the ecological implications required further assessment (Rissik, 2014). Kidd et al. (2015) further concluded that the negative impacts of a barrage increased as the location neared the coast. Our case-studies show that a TEB installed into the Tamar River estuary (or any other estuary) would provide insufficient benefits to outweigh the disadvantages in terms of mitigation of sea-level rise. An installation in the lower estuary would protect up to 60 km of upper estuary but exacerbate the problem in the remnant estuary from a greater tidal range and an atrophied bathymetry. An installation in the upper estuary would arguably protect the city of Launceston with severe degradation of the remnant estuary. A permeable barrage seems more appropriate; as with La Rance, Thames, and Moncton (post 2010)

4.6 Tidal range implications

The possibility of a tidal amplitude increase warrants further scrutiny. Prandle (2009) derived the following equation for the estuarine length; $L = 2980\ (Q \tan \alpha / f\, \varsigma^*)^{1/2}$, where Q is river discharge, $\tan \alpha$ is the side slope gradient, f is the friction factor and ς^* is the tidal amplitude. For a barrage installation, L decreases, Q, $\tan \alpha$ and f remain constant, at least in the short term, and therefore tidal amplitude ς^* must increase. In theory at least this increase could be large. As the migration continues, the estuary becomes shallower and f increases so that the tidal amplitude will begin to reduce, perhaps back to pre-barrage levels. When mitigation of SLR is the main objective, tidal range amplification is counterproductive.

5. Conclusion

In recent years SLR has become an increasing concern in terms of coastal management and existing TEBs are seen as beneficial mitigators, even though this was not part of their original design purpose. Using four examples of existing TEB installations, we have shown that the morphological impacts, which can be severe, can be effectively modelled using FORM and that this provides a useful tool to predict the outcomes of new TEB installations. Detrimental outcomes must be carefully evaluated by estuarine and coastal managers against perceived benefits from SLR mitigation.

The four test sites represent increasing complexity; the Petitcodiac River is basically a single stretch of estuary with little intertidal and no major tributaries; the Avon River has major tributaries; the River Tees has major anthropogenic adjustments to the intertidal, length, and dredging; and La Rance is complicated by two barrages and ongoing dredging. Regime has been re-established in the Petitcodiac, Avon and La Rance estuaries whilst on-going dredging in the Tees has halted the onset of a new regime. Despite this increasing level of complexity, in each case evidence was presented to support our hypothesis that none provide justification for installation of a TEB in the Tamar River estuary to mitigate SLR.

6. Acknowledgements

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CHAPTER 6:

BATHYMETRIC REJUVENATION STRATEGIES FOR A MORPHOLOGICALLY DEGRADED ESTUARY

Abstract

Bathymetric adjustment of estuaries created by anthropogenic stressors is a common global issue. Typical stressors are tidal levees, jetties, infilling, barrages and flow redirection. Removal or alleviation of stressors should in part, reinstate previous conditions. Generic and site specific rehabilitation strategies were assessed using a simple regime model (FORM) for the excessively silted Tamar River estuary in Tasmania, Australia. The model calculated the net sediment adjustment resulting from each strategy and was applied to evaluate projects designed to mitigate previously identified stressors and two separate barrages. Results show that a combination of projects involving removal or mitigation of stressors potentially eroded $>7*10^6$ m^3 of silt over the study area whereas both barrages caused silt accretion, one potentially doubling the volume of silt accumulated since the early 1800s. It was concluded that a substantial rejuvenation of the estuary was possible utilising various strategies, including creating a tidal lake, removing tidal levees, reconstituting an old meander system, and creating an additional waterway, whilst mainly negative trade-offs would result from installation of a barrage. In a general sense, the recommended strategies would apply to similarly degraded estuaries elsewhere.

Key words

silt accretion, remediation, stressor, hydrodynamics, total exclusion barrage

1. Introduction

Environmental degradation of estuarine systems is a common global problem arising from multiple anthropogenic stressors including pollution, loss of riparian vegetation, alteration to hydrodynamics by levees and restrictions to silt movement (causing sediment accretion or erosion), urban and waterfront development, and sewage effluent (Moss et al., 2006). Many estuaries in the UK (e.g. the Hubble, Tees, Humber and Thames) and Europe have been restricted to the extent that they are now effectively tidal canals, with some changes dating back to Roman times (Morris and Mitchell, 2013). Bathymetries are restricted by hard-walled levees, and flows have been decimated by loss of storages, barrages and weirs (Morris and Mitchell, 2013; Morris, 2013). Urban development on old intertidal flats means that hysteresis (Suding and Hobbs, 2009) is now present and restoration to a previous state is not possible. In the USA the non-regulatory National Estuary Program (NEP) works *"to* *improve the waters, habitats and living resources of 28 estuaries across the country"* (https://www.epa.gov/nep accessed July 2016). Projects span the east and west coasts and Puerto Rico. In the late 2000s restoration of rivers lakes and estuaries was a $2billion per year industry in the USA with 64 dams removed in 2008 (http://www.water.ca.gov/fishpassage/docs/dams/dams08.pdf accessed July 2016). Williams et al. (2002) cite an early example from 1637 in the town of Cley in Norfolk, England where dyke removal and thus an increased tidal prism was recommended to flush sediment from the estuary.

Any increase in the tidal prism equates to the same volume of silt lost from the inter-tidal zone; it is a 1:1 zero sum game (Kidd and Fischer, 2016) assuming tidal range is unaffected and tidal prism exchange with ground water is negligible. The tidal prism is the action and the silt loss is the reaction. The reverse is not true as equilibrium can only re-establish by further silt accretion (Davis and Kidd, 2012; Dennis et al., 2000). Kidd et al. (2016a) developed a simple first order response model (FORM) to describe coastal-plain estuaries with boundary conditions of convergence, synchronicity, tidal range, storage volumes of intertidal flats, the tidal prism of tributaries and river width. FORM calculates the bathymetric change in terms of sediment volumes following permanent adjustment of a boundary condition.

The Tamar River estuary in Tasmania, Australia has been subject to multiple anthropogenic stressors resulting in the loss of important ecosystem services and values (Davis and Kidd, 2012). The degradation which has occurred since European settlement in 1806 is typical of degradation over many hundreds of years (to millennia) in other estuaries around the globe. In the Tamar, two major stressors have been identified: a reduction of the tidal prism in the main estuary due to extensive canalisation of the upper estuary; and the loss of freshwater flow from a major tributary (due to diversion for the generation of hydroelectricity). Sustainable remediation strategies which address these stressors have been suggested by Davis and Kidd (2012) including, a tidal lake, reinstatement of tidal wetlands (by removal of dykes/ levees) and redirection of power station outflow. In a general sense and depending on the nature of the stressors, the strategies modelled in this study are equally applicable to estuaries elsewhere. On their website PIANC (2011) state that 'working with nature gives a good chance of (project) success, whereas working against nature guarantees failure', which is essentially the rationale of Davis and Kidd (2012); remove the stressors and let natural processes take their course.

As a preliminary evaluation of the proposals of Davis and Kidd (2012), FORM was used to predict bathymetric outcomes over the upper most 32 km of the Tamar River estuary (the silt belt) and give a prognosis for four specific trouble spots in the upper estuary. In addition, a new meander system and two barrage installations were considered. The aim was to identify those strategies having a high probability of success, whilst identifying trade-offs of other proposals which do not address the known stressors. Implications for asymmetrical tides, existing storages and other ecosystem services are considered.

2. Methods

2.1 Site Description

The Tamar River estuary in Tasmania, Australia comprises three distinct waterways, the estuary and two major tributaries, the North and South Esk Rivers (Fig. 6.1). The North Esk is tidal for ~11.7 km with a tidal prism of 1,700,000 m^3 making it the more dominant of the tributaries and is, in reality, a continuation of the main estuarine channel. For the purposes of this study, the South Esk River is the first tributary and the Tailrace is the second tributary. The Esk Rivers meet at the city of Launceston (population of 90,000), approximately 70 km upstream of the estuary mouth. The lower ~30 km is a ria, confined by the bed rock of a horst and graben structure, whereas the upper estuary has the funnel-shape of a coastal-plain estuary which flows through softer silts and clays. The study area is from the high tide boundary in the North Esk River (0 m) to the limit of the silt belt 32 km downstream (Rosevears).

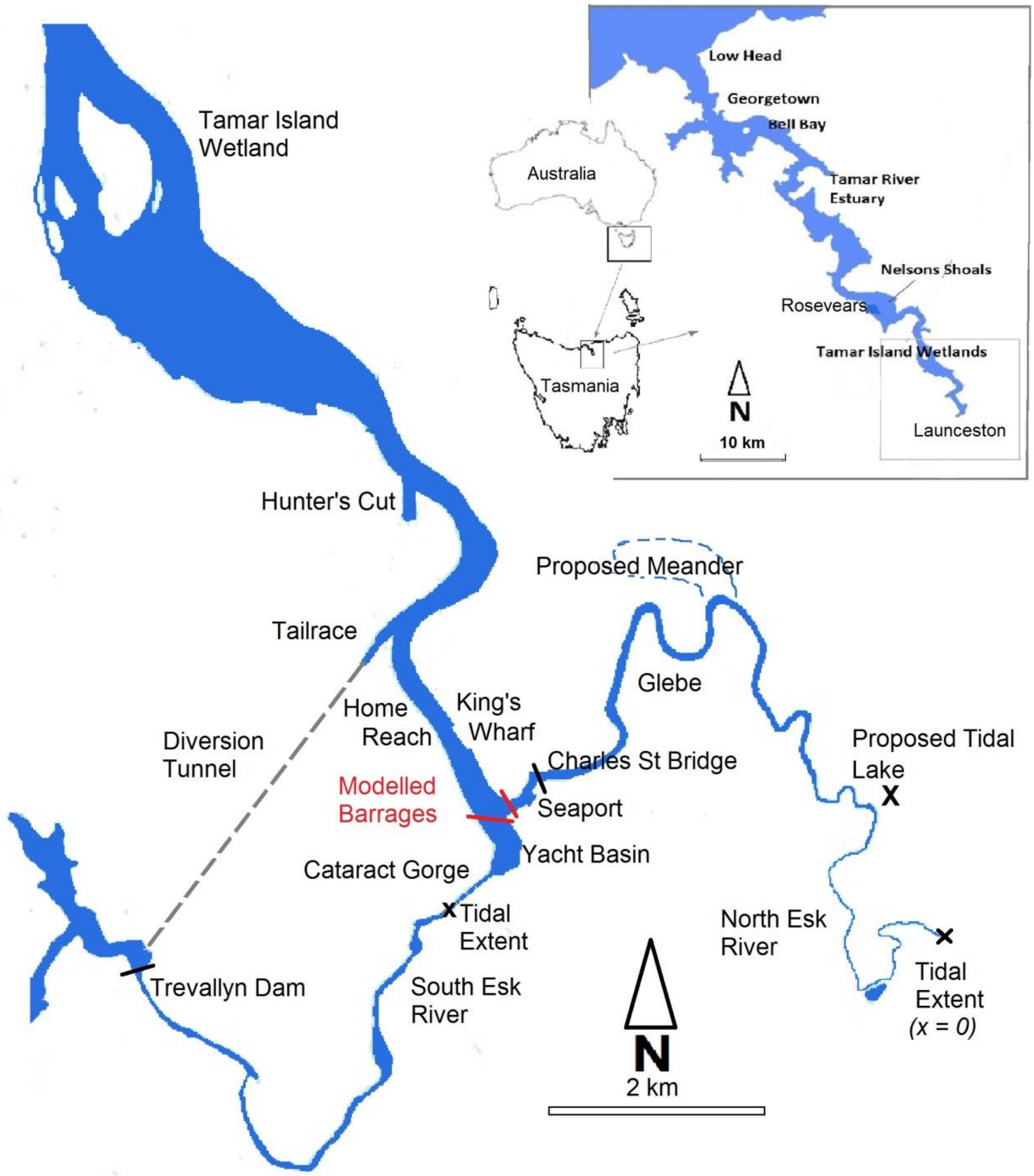


Fig. 6.1 Location of the Tamar River estuary in northern Tasmania, Australia.; The silt belt is from Rosevears to approximately the position of the proposed tidal lake

The estuary was classified as a mesotidal drowned river valley by Edgar et al. (2000). Tides are hyper-synchronous (Dyer, 1997; Kidd et al., 2014) and increase from 2.34 m at the mouth to 3.25 m at Launceston (Foster and Nittim, 1987). Flow velocities are asymmetrical with flood tides peaking at 0.4 $m.s^{-1}$ and ebb tides reaching 0.3 $m.s^{-1}$ (Foster et al., 1986) although higher velocities (~0.6 $m.s^{-1}$) were recorded by Kidd and Fischer (2016) as the system neared equilibrium. Sediment which has flocculated at the salt water boundary is carried upstream and deposited in the upper Tamar River estuary, lower South Esk (Yacht

Basin) and lower North Esk estuary, but only in times of low freshwater inflows (Foster et al., 1986), (Fig. 6.2). At equilibrium this effect is balanced by the combined mechanisms of dwell at high water and high velocities before low water which induce sediment flux in the downstream direction (Kidd and Fischer, 2016).

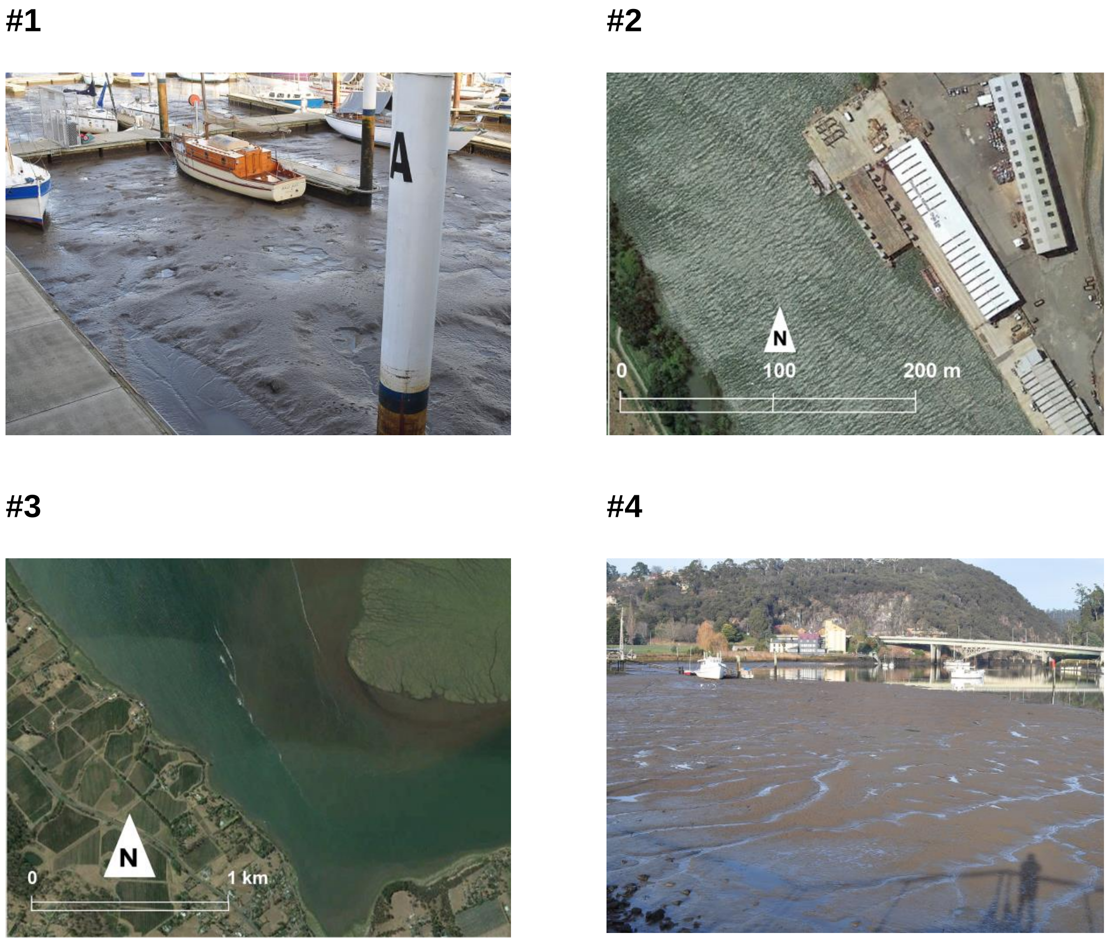


Fig. 6.2 Sites requiring remediation in the upper estuary, Site #1 The Seaport marina showing silt accretion (~11000 m from the high tide boundary), Site #2 Ship lift at Kings Wharf where depth is a problem (12700 m), Site #3 Rosevears where depth is a problem (27 km), Site #4 The Yacht Basin, the first tributary where silt accretion has resulted in loss of amenity (~11,700 m). Images 2 and 3 are sourced from Google Earth

Drinking water is drawn from both Esk Rivers and the Trevallyn Dam on the South Esk River feeds water to a hydro-electric power station via a diversion tunnel. The outflow from the station meets the estuary at the Tailrace (Fig. 6.1). Prior to the building of the Trevallyn Dam (1955) and the flow redirection through the Tailrace, the South Esk River flow varied from a monthly mean of ~20 m^3s^{-1} in years of low rainfall, to ~150 m^3s^{-1} during years of high rainfall (Foster et al., 1986). The mean power station use is 50 m^3s^{-1} which includes 20 m^3s^{-1} due to an inter-basin transfer. In 2011 the power station operators (Hydro Tasmania) increased discharge through the Cataract Gorge from 1.5 m^3s^{-1} to 2.5 m^3s^{-1} for environmental reasons, although the legal requirement is only 0.43 m^3s^{-1}.

Secondarily treated effluent from a waste water treatment plant enters the estuary opposite the power station outflow at Ti-tree Bend and from several other sites. The upper reaches of the estuary have undergone considerable in-filling, realignment, and draining (Davis and Kidd 2012) resulting in a ~30% loss of tidal prism since settlement. Reduction of flow in the first tributary is a major stressor as is the realignment of the mouth of the North Esk River. The stressors combined with the cessation of dredging in the 2000s, have resulted in excessive silt accretion as the estuary establishes a new equilibrium between the tidal flows and cross-sectional areas. This causes problems at (Site #1) the Seaport marina 11.5 km from the tidal limit of the North Esk, (Site #2) Kings Wharf (12.5 km), (Site #3) Rosevears (27 km) and (Site #4) the Yacht Basin (11.7 km) (Fig. 6.2).

The study area includes Tamar Island wetland (Fig. 6.1) between 17 km and 22 km from the head which has undergone a huge silt accretion since settlement (Fig. 6.3). This is an important habitat for migratory species which are protected by the Japan Australia Migratory Bird Agreement (JAMBA) and the China Australia Migratory Bird Agreement (CAMBA). In the early 1900s, excavation commenced on a diversion across Stephenson's Bend; known as Hunter's Cut (Fig. 6.1). The objective was to mitigate flood effects but the attempt failed due to instability of the banks.

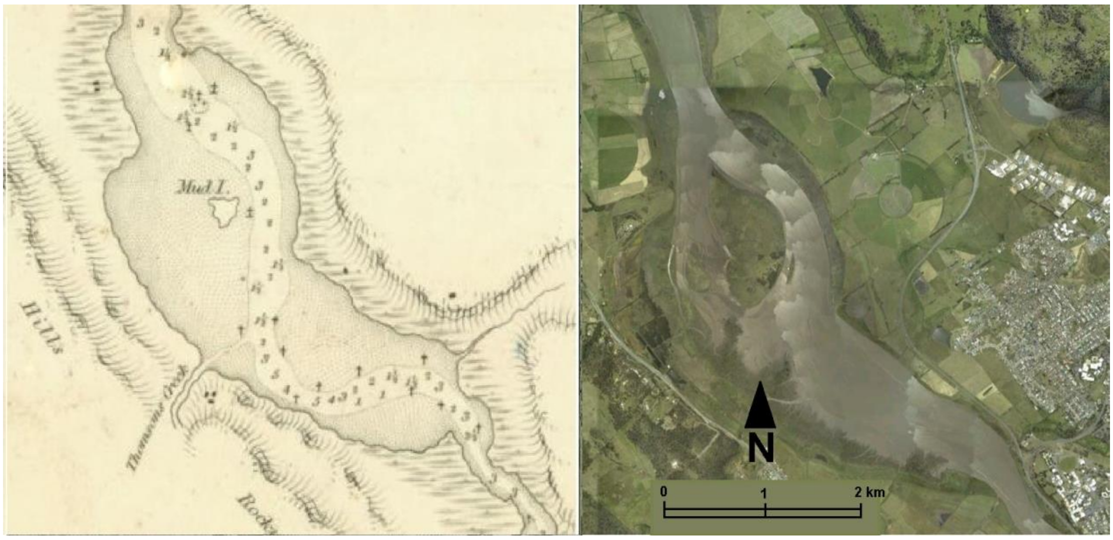


Fig. 6.3 Tamar Island wetlands in 1830 (left) (Welsh, 1830) and 2015 (right), showing massive silt accretion (source Google Earth)

A floating marina at the mouth of the North Esk is severely affected by silt (Fig. 6.2). Rowing and sailing have been seriously curtailed, and soft mud banks represent both a physical and health hazard (BMT_WBM, 2008; Seen et al., 2004). Studies have been commissioned (BMT_WBM, 2008; Foster et al., 1986) on the silt accretion issue with recommendations including: do nothing; run the power station against the flood tide; continue dredging; and installing a barrage. Davis and Kidd (2012) rejected each of these and suggested projects acting against the stressors they identified in the system.

Visually, the first tributary (the Yacht Basin) appears to be the main estuary but this is not the case (Fig. 6.4). Foster and Nittim (1987), disregarded the influence of the main estuary from 0 m to 11,700 m (the North Esk River) because of the small watershed and riverine flow <10 m^3s^{-1} compared with the combined discharge of the first and second tributaries >50 m^3s^{-1}, emanating from a much larger watershed. However, the first and second tributaries have lesser influence on estuarine hydrology due to the small tidal prism of each, albeit floods through the Cataract Gorge are the major scouring mechanism for the Yacht Basin and Home Reach. Suspended sediment concentrations increase as a power function of river discharge (Campbell and Bauder, 1940), so Foster and Nittim (1987) were correct in that most silt enters the estuary through these tributaries but the large tidal prism of the main estuary (the North Esk River) provides the greatest influence on the equilibrium position.

This is a paradigm shift in the understanding of the hydrology, sedimentary processes and problems in the estuary.

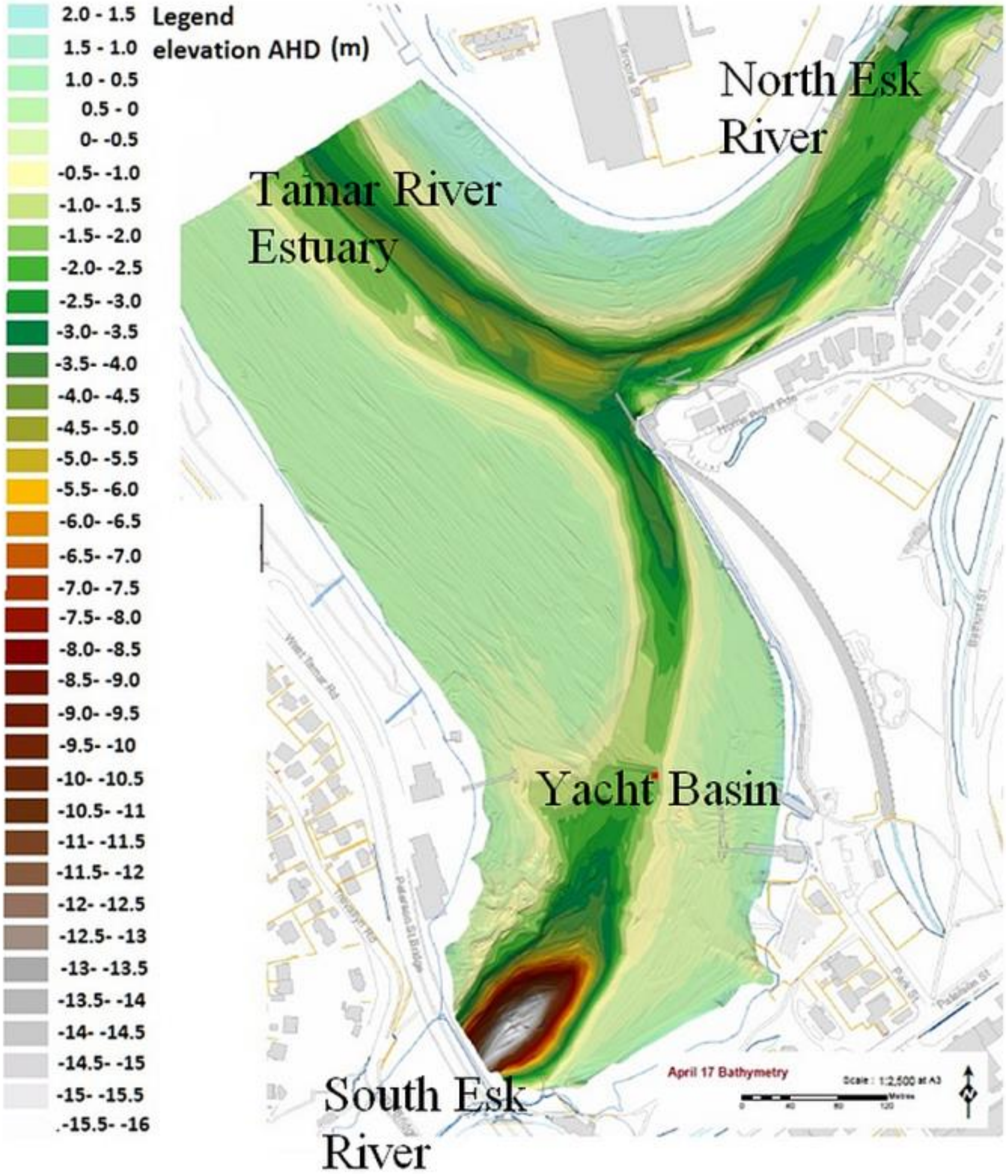


Fig. 6.4 A bathymetric survey (April 2012) of the first confluence indicating the continuation of the main estuarine channel in the top right (North Esk River, tidal for ~11.7 km). The deep hole at bottom centre is due to flood scour. The tidal channel of the Yacht Basin and Cataract Gorge (South Esk River) ends ~400 m beyond the area depicted limiting the tidal prism of the tributary to ~380,000 m3 compared to ~1,700,000 m3 in the North Esk River (bathymetric data courtesy Launceston Flood Authority)

2.2 The model

FORM is a top-down regime model (Emphasys Consortium, 2000) and considers only the initial and final equilibrium conditions. Equilibrium is defined as a state of zero net sediment flux (Dyer, 1997) or has a steady bottom profile (Schuttelaars and de Swart, 2000) and FORM assumes only one morphodynamic equilibrium is possible. The bathymetric ramifications for each strategy were modelled by adjusting the corresponding boundary condition, which for the strategies considered in this study, was an adjustment of the tidal prism at the point of implementation of each strategy at distance x; where x is measured from the tidal limit of the North Esk River ($x = 0$).

The essence of the model is as follows (Kidd et al., 2016). The model develops plan-form parameters of channel width against distance from the tidal extent (head). A baseline, simple power equation is developed for the breadth (at mean tidal level) of the main channel against length and a second (linear) equation is developed for the tidal range against length. The product of the two equations at distance x gives the tidal cross-sectional area which when integrated from 0 to x gives the tidal prism at distance x. Kidd et al. (2016) used 100 m intervals to develop a table of breadths and tidal prisms for x = 0 to 32,000 m, although smaller intervals could be used. The tidal prisms of tributaries and storages are estimated and added to the model by reading the resultant width from the table for the combined tidal prisms. This allows for the existing bathymetry to be modelled and also any bathymetric adjustment resulting from changes to tidal prism at any distance x from the head. The model is limited to ~30 km and does not consider the effect of tidal prism forcing (anthropogenic) on tidal range. Nevertheless the model was in close agreement with Tamar River estuary widths ($R^2 = 0.85$, $p < 0.001$). The model calculates Δx to be the nearest least multiple of 100 m and subsequently the calculated silt volume removed is conservative.

The model calculates the tidal prism increase which equates to the silt lost from the intertidal zone (given the assumptions and limitations previously mentioned including, tidal range being unaffected, negligible tidal prism exchange with ground water and the modal extent being limited to ~30 km over which the tide is contemporaneously full) (Kidd et al., 2016a). Silt lost from the channel below MWL was estimated using the methodology of (Kidd et al., 2016a) and O'Brien's equilibrium equation (O'Brien, 1966) as modified by (BMT_WBM, 2008). Although not strictly an equation due to being dimensionally incorrect, the relationship is, $A = 0.0031*P^{0.81}$; where A is the cross sectional area below half tide (m^2) and P is the tidal prism (m^3). The co-efficient and exponent are highly variable from system to system. Change to silt volume between two sections was estimated from the product of the average of the two cross sectional area increases and the distance between them; this figure plus half the tidal prism change gives an estimate of the total silt accreted or eroded between two stations (Kidd et al., 2016a).

2.3 Evaluation of remediation strategies

FORM was used to evaluate several remediation strategies (Fig. 6.5), a tidal lake, removal of tidal levees, increasing the length of the estuary by reinstating an old meander system and a combination of each. A barrage on the main estuary near the first confluence was also considered. Four scenarios were considered for the first tributary, which included combinations of extending the Tailrace via a new waterway and installing a tidal barrage (Fig. 6.6). A tidal prism was calculated for each strategy and the seaward estuarine width calculated accordingly by FORM.

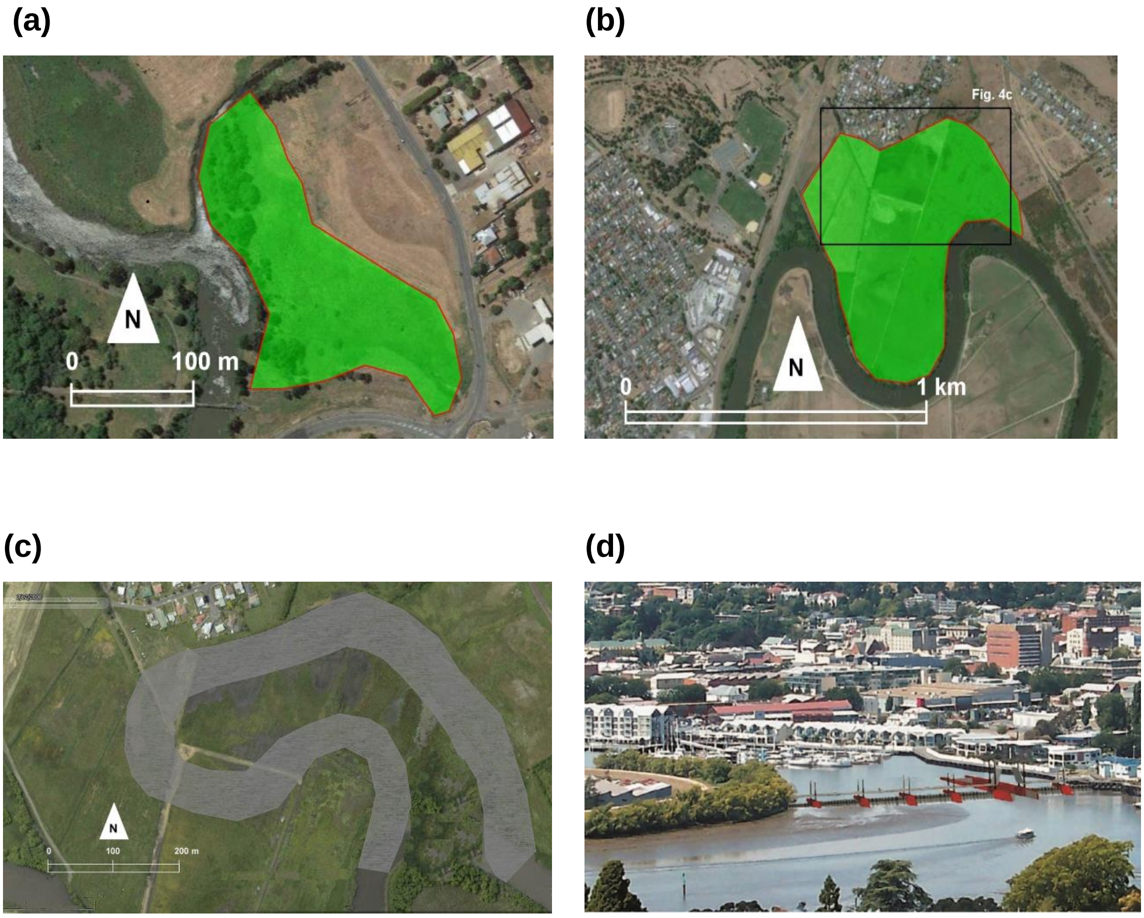


Fig. 6.5 Modelled strategies for the main estuary; (a) a tidal lake of 50,000 m^3 at 4,000 m; (b) tidal levee removal from 46ha of wetland partly protected by levees; (c) new 1 km meander; and (d) a total exclusion barrage at 11,700 m (Maloney, 2013).

Removal of the levees and the proposed meander increase the local tidal prism by ~265,000 m^3. Images (a), (b) and (c) sourced from Google Earth

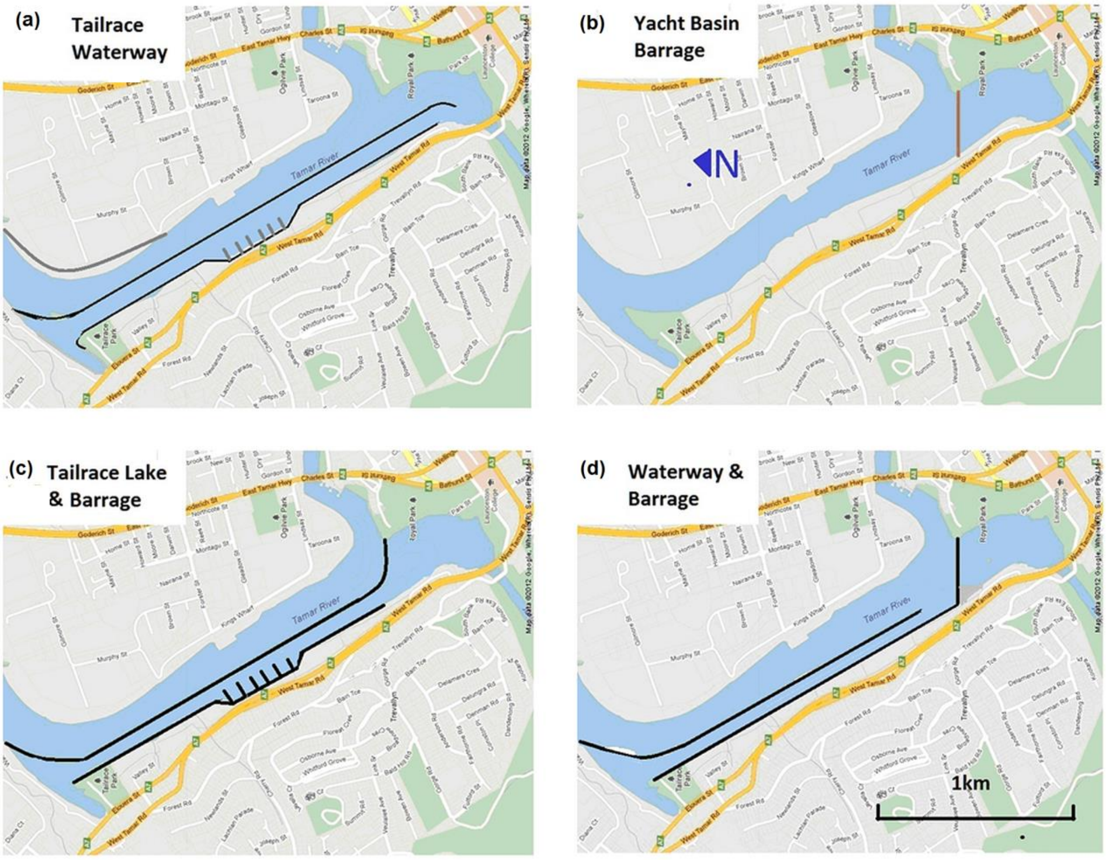


Fig. 6.6 Four conceptual solutions to Yacht Basin silting

2.4 Strategies in the main estuary

2.4.1 Tidal lake

A hypothetical tidal lake was modelled at x = 4000 m with a tidal volume of 50,000 m^3 (Fig. 5a).

2.4.2 Removal of tidal levees

The modelled area between x = 7500 m and x = 8500 m is partly protected from tidal inundation by a series of internal dykes (Fig. 6.5b). The area to the top left is arable pasture; the remainder receives some tidal exchange with the estuary. The increased inundation resulting from removal of these levees was estimated and added as tidal prism to FORM at a distance of x = 8000 m.

2.4.3 Increased tidal length

A close examination of the inundated area in Fig. 6.5b shows an old meander system and the remnants of an oxbow lake (Fig. 6.5c). The effect of re-instating this system and allowing the neighbouring tidal flat to inundate during spring tides was modelled by adding the estimated tidal prism as a point source (see supplementary material). An alternative method is to increase the estuarine length in the model (which adds the tidal prism of the new meander to the system) and including the additional tidal prism of the tidal flat inundation.

2.4.4 A total exclusion barrage

A total exclusion barrage near the first confluence (Fig. 6.5d) has been suggested (Maloney, 2013). Proponents have called this structure a weir, which in Australia is a term usually applied to a small dam across a river, but this site is estuarine. We have modelled it as a standalone strategy. The ramifications for silt volume of the structure are modelled by removing the tidal prism of the North Esk River (~$1.7*10^6$ m^3) at 11,700 m.

2.5 Strategies in the first tributary

Strategies in the first tributary involve a barrage across the waterbody and a waterway which redirects the second tributary (The Tailrace) to the first tributary (South Esk River). Various combinations are considered (Fig. 6.6). The waterway was modelled for various widths which influences the tidal prism added to the system. Also discussed are implications of increased water releases from the Trevallyn Dam through the Cataract Gorge.

The effects of each remediation at Figs. 6.5 and 6.6 are summarised with particular reference to three trouble spots; (#1) the Seaport at 11,500 m, (#2) Kings Wharf at 12,500 m and (#3) Rosevears at 27,000 m. A total remediation package comprising a lake, removal of levees, a meander and a waterway is also modelled, which includes the fourth trouble spot, (#4) the Yacht Basin.

3. Results

3.1 Tidal Lake

A tidal lake of 50,000 m^3 at 4,000 m produces a compounding increase in the tidal prism throughout the estuary (Table 1). The increase at 32 km is ~$2.12*10^6$ m^3, where the cross sectional area increases from 4155 m^2 to 4244 m^2.

Table 6.1 Net tidal prism ($10^3 m^3$) change at equilibrium for known trouble spots due to each remediation strategy

Strategy	Trouble spot #1 Seaport Marina at 11,500 m ($10^3 m^3$)	Trouble spot #2 Kings Wharf at 12,700 m ($10^3 m^3$)	Trouble spot #3 Rosevears at 27,000 m ($10^3 m^3$)	Trouble spot #4 Yacht Basin at 11,700 m ($10^3 m^3$)
Existing tidal prism	1,613	2,744	26,400	380
Tidal lake	+273	+312	+980	No change
Tidal levee removal	+240	+272	+852	No change
Meander+levee removal	+443	+510	+2,012	No change
Combination lake+levee+meander	+735	+843	+2,800	No change
Tailrace waterway (40 m wide)	No change	+371	+763	+345*
Tailrace lake and Y. B. barrage	No change	-434	-1,500	-393*
Tailrace waterway and Y.B. barrage	No change	-45	-385	-41*
Yacht Basin barrage	No change	-433	-1,288	-393
Combination lake+levee+meander +waterway	+824	+1,284	+3,020	+842
N. Esk Barrage	Constant Water level	-1,968,	-6,380	No change
Return to natural flows through Cataract Gorge	No Change	<186; varies with flow rate	No change due to contraction of Tailrace	<155; varies with flow rate.

***175 X 10^3 m^3 removed at 13700 m due to loss of Tailrace**

3.2 Losses from the channel due to the tidal lake

The section of estuary between the second tributary (Tailrace) and the Charles St Bridge represents the bulk of the amenity available to the city. Calculations of the volume of silt removed from this section due to a tidal lake are at Table 6.2.

Table 6.2 Total calculated losses from the main estuary due to a 50,000 m^3 tidal lake at 4000 m. The target section is 11,000 m (Charles St Bridge) to 13,700 m (Tailrace confluence). The section includes the trouble spots of Seaport (~11,500 m) and Kings Wharf (12,700 m) and together with the first tributary (the Yacht Basin) provides the bulk of the amenity to the city of Launceston. Calculation of volume increases are within the sub-boxes

	Existing TP (10^3m^3)	Existing x-area (m^2)	New TP (10^3m^3)	New x-area (m^2)	Increase x-area (m^2)	Volume increase (10^3m^3)	Totals (10^3m^3)
First confluence	2,358	449	2,661	496	47	303	
Tailrace confluence	3,166	571	3,530	623	52	364	
Average increase in x-area					50		
Volume increase over 2km (below half tide)						100	
Increase above half tide						30.5	
Sub total volume increase							130.5
Seaport	1,610	330	1,893	377	47	283	
Chas. St Bridge	1,455	304	1,719	348	44	254	
Volume increase below ½ tide (Chas. St Bridge. to NE mouth) (500m)						22.75	
Volume increase above half tide						14.5	
Sub total							37.25
Grand total Chas. Br. To Tailrace							**167.75**

3.3 Removal of tidal levees

Removal of tidal levees between 7500 m and 8500 m would inundate the area at Fig. 6.5b to a depth of 500 mm at mean high water (MHW). The net increase of the tidal prism is approximately 100,000 m^3. Assuming a point source increase at 8000 m then the tidal prism increase over the silt belt is 615,000 m^3 (Table 6.1), which equates to the volume of silt removed from the intertidal banks. Another $1.010*10^6$ m^3 are removed from the channel below MWL and the net effect of the strategy is removal of $1.317*10^6$ m^3 (615000/2 + 1,010,000) over the silt belt.

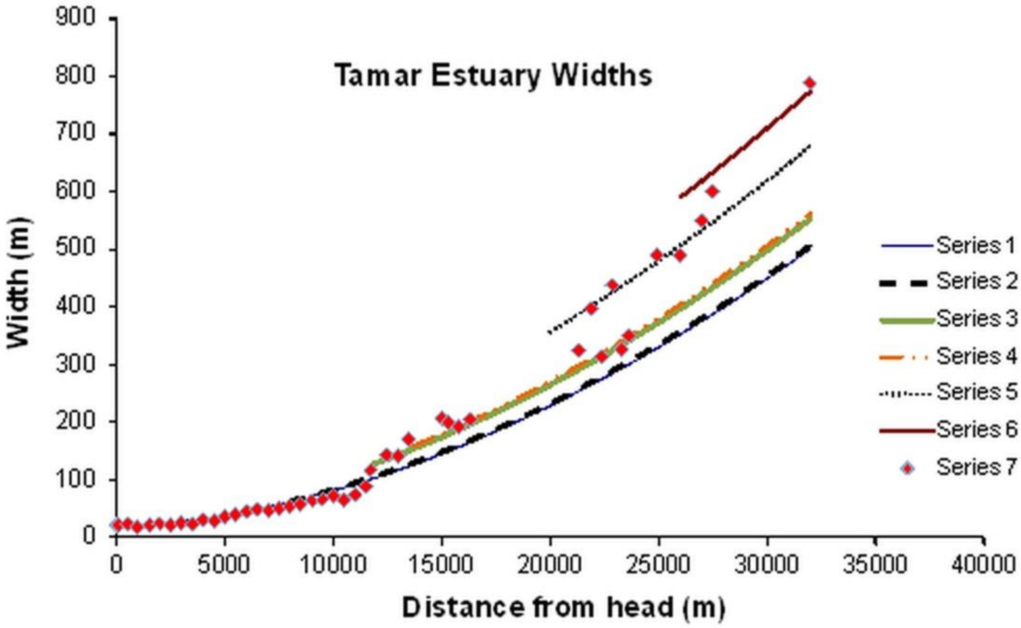
3.4 Increased sinuosity of the meander system

Reconstituting the old meander (Fig. 6.5c) increases the tidal prism at 8000 m by 220,000 m^3. This remediation requires the removal of tidal levees and the net increase in tidal prism is 320,000 m^3 (Table 6.1). The tidal prism increase at 33,000 m (32,000 m for the original system) is $1.653*10^6$ m^3 with $3.729*10^6$ m^3 of sediment removed.

3.5 A total exclusion barrage at the mouth of the North Esk River

This strategy removes the tidal prism at 11,700 m causing contraction of all widths to seaward (Fig. 6.7 series7). The first tributary effectively becomes the main estuary with a tidal prism of ~380,000 m^3 at the barrage. The contraction (Fig. 6.7b) amounts to a tidal prism loss of 1.7 million m^3 (Table 6.1) at the barrage and a decrease of tidal prism of $6.8*10^6$ m^3 over the silt belt. The total silt accretion is $12.327*10^6$ m^3.

(a)



(b)

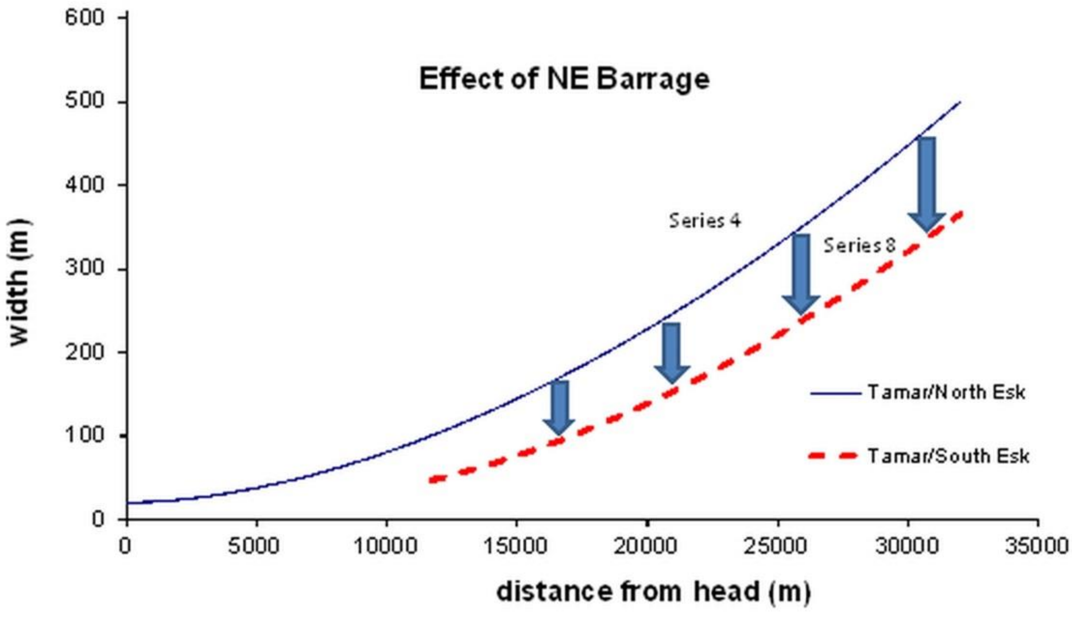


Fig. 6.7 FORM results showing (a) influence of each waterbody and sampled widths and (b) contraction of series 4 to series 8 due to a total exclusion barrage at the first confluence. Series 1 Extrapolated influence of main estuary (equation 1); Series 2 Influence of remnant wetland (+60,000 m^3); Series 3 Influence of first tributary (+600,000 m^3); Series 4 Influence of second tributary (+175,000 m3); Series 5 Influence

of first storage (+3,900,000 m3); Series 6 Influence of second storage (+5,040,000 m^3); Series 7 Sampled widths; Series 8 Contraction of series 4 (extrapolated) due to a barrage at 11700 m

3.6 Strategies in the first tributary (Yacht Basin)

3.6.1 Second tributary (Tailrace) waterway

The hypothetical Tailrace waterway (Fig 6.6a) redirects the power station discharge to the trouble spot in the first tributary (the Yacht Basin). Whilst the additional riverine flow is advantageous, the tidal prism developed by the waterway is the main driver for estuarine rejuvenation and this will vary with the width and length of the waterway. For a waterway of length 2.2 km, width 60 m, and tidal range 3.25 m, the tidal prism is 429,000 m^3. For modelling purposes 600,000 m^3 is used to account for additional scouring of the Yacht Basin and Trevallyn tidal flats, whereas the existing tidal prism of the Tailrace is lost to the system. A waterway removes ~263,000 m^3 over Home Reach (x = 11,700 to 13,700 m) and 3.039*10^6 m^3 over the silt belt.

3.6.2 First tributary barrage

A standalone Yacht Basin barrage (Fig. 6.6b) removes a tidal prism of 380,000 m^3 at 11,700 m and increases the silt accreted over the silt belt by 2.800*10^6 m^3.

3.6.3 Second tributary lake and barrage

A tailrace lake and barrage across the South Esk River (Fig. 6.6c), removes the tidal prism of both tributaries, i.e. 380,000 m^3 at 11,700 m and a further 175,000 m^3 at 13,700 m. The net effect over the silt belt is 5.176*10^6 m^3 of silt accreted.

3.6.3 Second tributary waterway and first tributary barrage

The waterway exiting in front of a barrage (Fig. 6.6d) provides a net loss in tidal prism of 55,000 m^3 at 11,700 m and 0.836*10^6 m^3 of silt accreted over the silt belt.

3.6.5 Increased flows through the Cataract Gorge

The alternative to the waterway discussed above is to increase the discharge from Trevallyn Dam to mimic historical flows. This would allow for the inter-basin diversion of 20 m^{3}s^{-1} to be utilised by the power station. The loss of generation revenue is likely to be AU$18million per annum. It is estimated that the additional flow will increase the low water channel through the Yacht Basin tenfold whereas the tidal prism increase is likely to be modest and capped at the present volume of silt above low water level (LWL). An increase in tidal prism of 100,000 m^3 to 480,000 m^3 erodes 865,000 m^3 of silt over the silt belt and an additional 228,000 m^3 over Home Reach.

4. Discussion

The model highlighted several strategies which would assist in the rejuvenation of the upper Tamar River estuary and would be beneficial in other estuaries. Each viable solution mitigates one or other of the stressors identified by Davis and Kidd (2012) and reinforces their findings that a barrage was not a viable solution to the problem of excessive silt accretion. The model proved useful in identifying strategies which warrant further 2D or 3D modelling (Emphasys Consortium, 2000) or which could progress under the guise of adaptive management (Thom, 2000; Walters, 1986). The local community must first decide the eco-system services they require from the estuary and then assess which sustainable remediation and ongoing maintenance programs will provide that amenity.

Apart from the barrages, the remediation strategies modelled all represent sustainable solutions to the problem of excessive silt accretion. They are designed to increase the tidal prism of the estuary, act directly against the stressors identified by Davis and Kidd (2012) and there should be no ecological surprises from their implementation (Gordon et al., 2008). The barrage in the main estuary showed unacceptable trade-offs, but a barrage on the first tributary could be considered with a compensating main estuarine strategy.

4.1 Strategies in the main channel (Tamar and North Esk Rivers)

4.1.1 Tidal lake

The position of the tidal lake is but one of many possible sites. It was chosen because it is publicly owned land, is low lying, will fill with fresh water that is already in the upper estuary and does not contain flocculated sediments, has the maximum compounding effect (Table 6.1), has excellent access from existing roads, is highly visible, provides a public amenity, and is surrounded by elevated land above the floodplain. There are some shortcomings; at ~ 1 km upstream of low tide boundary, the tidal range is only 2.5 m, whereas it is 3.5 m at the boundary; for the volume to be 50,000 m^3 then the area needs to be

2 ha; the larger area means more over-burden and under-burden (for depth at low tide); the total volume to be removed is 90,000 m^3. The model shows that a 50,000 m^3 lake in this position has the potential to permanently remove >2 million m^3 of silt from the study area, over that removed to form the lake (Table 6.2). The risk of the lake accreting rapidly is minimised because it will not be subjected to flocculated silt. Suspended silt in the riverine flow does not precipitate easily, and the dam on the first major tributary (Trevallyn Dam) shows no sign of fine sediment accretion. Hunter's Cut (Fig. 6.1) has not fully silted since its misguided conception 90 years ago, despite semi-diurnal inundation by tides with high flocculated sediment concentrations.

Existing hard-walling of the tidal levees (canalisation) will restrict the predicted tidal prism increase at the Seaport to some extent. However, the model shows a potential tidal prism increase at Seaport of >4 m^3 for every 1 m^3 of lake volume. In the absence of more sophisticated modelling, the lake would make a prime project to proceed under the guise of adaptive management, providing for close monitoring and a temporal component to the evolution. This would provide a template for further strategies, and a test of the FORM model.

4.1.2 Tidal flat inundation by removing tidal levees

Tidal levees are common in estuaries around the globe and removal is not always possible due to the hysteretic effects of urbanisation and infrastructure developments. Removal of levees provides an opportunity to restore to an historical state with considerable ecological advantages (Elliott et al 2007) and precedents have been established both in the USA and UK (Williams et al 2002). Tidal flats have an important role in the connectivity between terrestrial and marine eco-systems (Boulton et al., 2014). By removing tidal levees, local eco-system services such as spawning areas for fish and feeding areas for birds are enhanced, as are downstream eco-system services such as physical and visual amenity of the lower North Esk River and Home Reach. Further, in a 1D model developed by van Dongeren and de Vriend (1994) and confirmed by field data, it was shown that large areas of tidal flats can reverse tidal asymmetry and alter net sediment transport from flood dominant to ebb dominant (Dronkers, 1986), which is implicit in the silt reduction capabilities of this and other strategies. Mean high water spring (MHWS) tidal height is ~1.9 m Australian Height Datum (AHD) (Kidd et al., 2014) which places the historical tidal flat below most high tides, producing a semi diurnal inundation for places without levees. Reinstating this inundation

(Fig. 6.5b) is a convenient method of increasing the tidal prism, albeit the target area is privately owned.

4.1.3 Extension of the meander system

Reconstructing the meander system (Fig. 6.5c) increases the sinuosity of the system without affecting the position of the high tide boundary. It has some advantages over a lake; the old channel remains largely intact so less excavation is required than for a lake of similar volume. In-fill is required at the old incision point and this will require hard-walling to prevent re-incision. The meander will find its equilibrium position over time and silt will not accrete within it. The new meander will have no tidal levees and the adjacent floodplain inundation is a bonus.

The combined effect of the above strategies is to increase the tidal prism at the trouble spot at 11,000 m (the Seaport Marina) by 580,000 m^3, which will increase the cross sectional area by 95 m^2 below half tide or an increase of ~1 m in mean depth; which is a desirable outcome. Some typologies predict a constant estuarine length approximating ¼ of the tidal wave length (Prandle, 2009; Wright et al., 1973). This may have implications for extending the meander system in that the extent of tidal intrusion may diminish. However, this point is not well defined due to vagaries of tidal heights (ETS Worldwide Ltd., 2015) resulting from variations of air pressure and wind strengths. Anecdotal evidence suggests that recent removal of riparian willows has extended the tidal limit. Other sites exist in the floodplain for possible meander reinstatement.

4.1.4 A barrage on the North Esk River

A barrage on the main estuary maintains a constant water level in the marina, arguably increasing the amenity provided, but the trade-off is downstream where impacts are negative. The model shows a deterioration of the equilibrium position of the inter-tidal banks of ~13 million m^3 less the 1.7 million m^3 behind the barrage (Table 6.2). An imbalance of this magnitude will result in rapid silt accretion (Morris, 2013) and would effectively trap silt recruited to the system; estimated to be 30,000 - 120,000 tonnes per year (Foster and Nittim, 1987).

Any barrage will act as an additional stressor on the system because it will impede tidal flow (Davis and Kidd, 2012; Kidd et al., 2015). The model confirms the nature and size of the trade-offs involved in installation of a barrage. As an order of magnitude, a barrage is similar to the combined effects of all anthropogenic stressors introduced since 1806.

The ramifications for eco-system services of a barrage on the North Esk River are discussed by (Kidd et al., 2015). Above the barrage, an increased functionality of the marina is a positive outcome but the conversion of a marine ecosystem to a freshwater eco-system has negative connotations. Below the barrage, the ramifications for eco-system services are negative with a much reduced channel width and depth reducing the physical and visual amenity.

4.2 First tributary (Yacht Basin) solutions

In the 1920s the mouth of the North Esk was effectively realigned by in-filling the southern half of the channel. The net effect was to increase the length of the first tributary by ~150 m, so that the affected length was neither integral to the main estuary nor subject to the full influence of the tidal prism. The historical cross section is no longer sustainable by the inferior tidal prism of the tributary, which is 380,000 m^3 compared to 2,080,000 m^3 for the main channel. Over that 150 m section, the sustainable cross sectional area has contracted from 406 to 102 m^2 resulting in 45600 m^3 of silt accretion below half tide. This combined with the silt accretion effects of the dam and diversion built in 1955, necessitates remediation strategies other than removing known stressors, i.e. hysteresis is present and mitigating strategies are required (Davis and Kidd, 2012).

A barrage across the first tributary would permanently inundate this silt. Flood waters would eventually move the silt body beyond the barraged lake and into the main estuarine flow. Alternatively, a waterway could discharge across the silt body reducing its volume substantially. The barrage across the main estuary has been costed at AUS$25 million (Maloney, 2013), so a longer barrage across the first tributary appears to be cost prohibitive; nevertheless it is included in the modelling.

Various combinations of a waterway and barrage are possible (Fig. 6.6, Table 6.3). A waterway should be designed to allow for reverse flow in times of a major flood, which could simply be a spillway at the northern end. A barrage would keep flocculated sediments at bay; turbidity would decrease and amenity would increase without change to the salinity regime. A lock would be required to provide access to slipways and for tourist vessels.

Table 6.3 Ramifications for ecosystems services of each strategy applied to the first tributary

	A Waterway	B Lake and barrage	C Waterway and barrage	D Barrage
Tidal prism outcome at confluence	+600,000 m^3	-380,000 m^3	+380,000 m^3	-380,000 m^3
Water quality	Improved; sewage effluent diluted	Fresh water; sewage effluent diluted	Fresh water, decreased oxygen; no sewage dilution in weir	Fresh water but decreased oxygen; no sewage dilution
Yacht Basin silt	Removed by waterway flow	Removed by waterway flow and flood scour	Removed by flood scour	Removed by flood scour
Implications for Ship Lift at 12,700 m	Much improved	Detrimental	Slight improvement	Detrimental
Visual amenity	Clear water flow through the YB; unsightly barrier at low tide	High flow over weir; unsightly barrier at low tide	Low flow over weir; unsightly barrier at low tide	Low flow over weir
Tourist amenity	Much improved	Lock system adds to cruise experience;	Lock system adds to cruise experience; Walkway/ bikeway across YB	Lock system adds to cruise experience; Walkway/ bikeway across YB
Community amenity	Improved sailing; rowing; new marina	Large freshwater lake; urban beach; swimming; sailboarding etc; new marina	Freshwater lake; urban beach; swimming; sailboarding etc; new marina	Freshwater lake; urban beach; swimming; sailboarding etc
Power Station efficiency	No change	Slightly reduced	No change	Slightly reduced
Conclusion	Attractive	Should not be considered without a main estuary solution	Attractive if storm water discharge and sewage relocated	Should not be considered without a substantial main estuary solution

Building a waterway is a major capital cost, some of which could be offset by value creation and (or) value capture (Bowman and Ambrosini, 2000; Lepak et al., 2007). Each effective project could be an opportunity for a land developer with win/win outcomes for the developer, the city and the environment. A waterway combined with all (effective) main estuary strategies is a comprehensive solution to problems throughout the estuary. The extra depth at problem site #3 (Fig. 6.2) is likely to be over 1 m, assisting the navigation of vessels to the ship lift at trouble site #2 (Fig. 6.2). The ship lift will undoubtedly require on-going maintenance of the river bed to ensure that the lift can descend to the design depth, but this should be less frequent, given that the cross sectional area is increased by 190 m^2 below half tide.

The plan-form of a waterway should not be parallel, but should mimic natural landforms to provide confidence in the sustainability of the design (Hood 2002). A waterway confined to the present width of 80 m and expanding to 100 m will place the banks under erosional pressure and hard-walling and a deep channel (5m at low tide) will be essential. Ideally the waterway would be as wide as possible to maximise the tidal prism, whilst allowing the maximum fresh water flow into the Yacht Basin to prevent the turbid estuarine water from entering the area.

4.2.1 Water releases from Trevallyn Dam

Extra water releases from Trevallyn Dam would have a positive effect with a wider and deeper Yacht Basin which mimics pre 1955 conditions (Fig. 6.8). The historical equilibrium of the Yacht Basin is best described as dynamic (Kidd and Fischer, 2016) with high silt volumes in the summer months or during drought when flows are low, and less silt build up during high flow months. No matter what the flow rate the possible increase to the tidal prism of the Yacht Basin is limited to the present volume of silt above LWL. According to LFA data, this volume is ~155,000 m^3. The net effect of this strategy is to permanently remove sediment from the Yacht Basin and Home Reach to the Tailrace with little influence elsewhere.

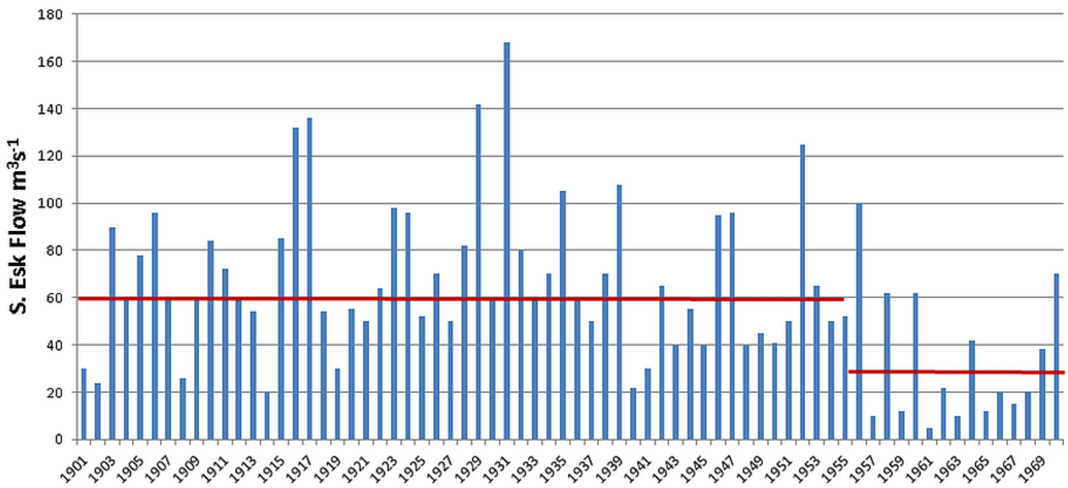


Fig. 6.8 Mean annual flow rates for the South Esk River through the Cataract Gorge from 1901 to 1970 (Foster et al., 1986). Prior to the installation of Trevallyn Dam in 1955 the average mean flow was ~ 60 m^3s^{-1}; dropping to ~30 m^3s^{-1} post 1955

4.3 Ramifications for Tamar Island Wetland

The model shows how remediation strategies in the upper estuary affect downstream sections. For those effective solutions, a reversal of the historic silt accretion can be expected at Tamar Island Wetlands (Figs. 6.1 and 6.3) with an equilibrium condition somewhere between the extremes of Fig. 6.3. More inter-tidal flats should evolve which are important feeding areas for migratory and other birds, but a return to the historical condition is unlikely, given the contemporary vegetation cover and eco-system services offered by Tamar Island Wetlands should remain much the same.

4.4 General Discussion

4.4.1 Channel scour

Monitoring by Launceston Flood Authority (LFA) shows that during floods most scouring occurs in the channel. This may not be true for increased flow, but it indicates that silt removed from the inter-tidal zone must at least match that removed from the channel. This is confirmed by Williams et al (2002) who found that channel equilibrial depth may temporarily be exceeded but it is eventually attained by slumping and erosion of the banks. Kidd and Fischer (2016) showed that the relatively large M6 tidal constituent in the upper Tamar produces erosional velocities before low tide, scouring sediment from the channel which is deposited on the banks at high water.

4.4.2 Siting of remediation projects

The model shows how the position of any remediation is important because of the compounding effect of permanent silt removal in the upper reaches. The bathymetry of an estuary, at least between confluences, can be predicted from any upstream cross section (Allen, 2000) which implies that the estuarine sedimentary and hydrological processes driven from the upper reaches are a major influence on bathymetry.

4.4.3 Flood levees

The LFA recently spent AU$S62 million on flood levees to protect the city from a 200 year flood. The remediation strategies in the upper estuary have the potential to increase the tidal velocity by ~35% in the short term, before equilibrium is re-established. This will require tidal banks to erode and care is needed to ensure that flood levees are not compromised, which is unlikely given the 200-year flood design criterion. The combined strategies of a tidal lake and a meander provide a solution giving maximum benefit without compromising the flood levees. The modelled lake is just one of many possibilities and multiples could be considered. The first tributary solution has no effect on levees, and a combination of all would mobilise large volumes of silt to the open sea (Bass Strait).

4.4.4 Response timescales

Although the model has no temporal component, Howard (1965) showed that a system out of equilibrium will re-establish equilibrium at a rate proportional to its distance from it, so that the new equilibrium will be approached asymptotically (Williams et al 2002). Observation following flood events, dredging and raking shows this to be true and so, the larger the strategy applied, the faster the initial adaptation. Recent raking moved >200,000 m^3 of silt downstream, approximately half of which returned within 8 months (Kidd and Fischer, 2016). By contrast, de Bok et al. (2001) showed an adaptation period of up to 30 years for a major system alteration in the Netherlands, and Williams et al (2002) showed systems continuing to evolve after 13 years. Whether scouring is by raking, flood, or a combination of both, successful strategies will prevent silt from returning after each scouring event until the new equilibrium is attained.

4.4.5 Implications for tidal range

More sophisticated modelling is required to gauge the effect on tidal heights of the strategies. Generally tidal heights increase as the tide flows up the estuary due to an ever narrowing channel. An opening up of a spill area at the head effectively widens the cross-sectional area, possibly diminishing tidal heights and providing a positive mitigation against sea level rise induced by climate change. Studies into the effect of the Herbrum weir on the Ems River estuary support this argument (de Jonge et al., 2014; Oberrecht and Wurpts, 2014; Schuttelaars et al., 2011).

4.4.6 Intertidal storages

The existence of storages in the Yacht Basin (Figs. 6.1 and 6.4), Tamar Island Wetlands (Figs. 6.1 and 6.3) and Nelson’s Shoals (Fig. 6.1), suggests that some process is acting to maintain them. Generally, they are orientated northwest to south east which aligns with the predominant wind direction and especially sea breezes in summer, and the cause is likely erosion by wind waves. The findings of D'Alpaos et al. (2010),who confined their field study to sheltered waters, indicated that this may be true. Dronkers (1986) found that wind waves may counteract the ability of tidal currents to build tidal flats by actively exporting sediment. Near high water, wind waves resuspend fine and coarse material which is differentially transported on the ebb tide. Coarse material is transported least but is less likely to be resuspended by the flood tide. The conclusion drawn is that these water bodies and their associated flats are more stable than generally assumed, play an active role in silt export, and are not the silt sinks claimed by Foster et al. (1986). Kidd et al. (2016a) assumed that the historical accretion on these flats could be explained by a lateral shift, so that the storage volume remained much the same, and the shift was due to the change in width of the associated channel. Stable estuarine systems tend to develop tidal flats with an area dependent on the total estuarine area (Williams et al., 2002), but the historical upper estuarine flats are now almost entirely lost to the Tamar system.

5. Conclusion

The modelling shows that sustainable remediation strategies in the study area are theoretically possible by removing or mitigating the stressors causing the problem. Strategies providing positive benefits are generally applicable to similarly degraded estuaries elsewhere; i.e. the removal of barriers to water and sediment movement will encourage maximum accommodation space and increase the tidal prism.

Other than the cases of standalone barrages, the modelled projects all act against known stressors and therefore no adverse hydrological, sedimentary or ecological surprises were expected. These strategies met the main objective of permanently improving the equilibrium position and thus removing silt and reversing degradation. They produce a net ebb sediment transport by reducing or reversing sediment flux asymmetry until equilibrium is established. Once implemented the strategies would require little maintenance and are therefore sustainable. The alternative is the non-sustainable practices of dredging and raking which require recurrent expenditures and do not favourably compare with the relatively cheap capital cost of these projects. For the Tamar, increasing the effectiveness of the South Esk discharge is an imperative either by dam releases or redirection of the Tailrace. The modelling has shown that historical losses of tidal prism can be largely restored if desired, by various combinations of sustainable projects.

This study highlighted the trade-offs in remediation activities which do not address the initial stressors and the examples modelled acted to exacerbate the silt accretion problem. Modelled projects showing potential could progress confidently under adaptive management, but where large capital outlays are involved, confirmation of predictions through numerical modelling of potential strategies, is recommended as a precursor to implementation.

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CHAPTER SEVEN:

GENERAL DISCUSSION

Overview

Firstly, a reminder of the research question:-

"What factors influence the morphological degradation of estuaries and in particular, the upper Tamar River estuary; is the process reversible and to what extent? What sustainable solutions or strategies could be applied to this and other similarly degraded estuaries?"

The question is basically the same as that asked of consultants and researchers over the last forty years or so, but which has gone unanswered because those studies failed to recognise silt as a symptom of the problem, whereas this study has the stressors (root-causes) identified by Davis and Kidd (2012) as central to the methodology. The simple metaphor of oil leaking from an engine (described in Appendix C) illustrates the futility of trying to understand a problem by studying the symptom; and managing a problem by removing the symptom.

In a similar vein, the premise that the Tamar is somehow unique has been the bane of restoration efforts for many decades whereas the approach in this thesis of looking for the similarities with other estuaries has led to the strategies discussed in Chapter 6. Characterisation as unique is an overstatement. The unusual geomorphology of the upper Tamar is discussed in the site descriptions of each paper and indeed similar problems in estuaries around the globe are cited. The Tamar has been classified as a meso-tidal drowned river valley (Edgar et al. 2000) but this definition does not apply to the study/problem area of the upper Tamar. This and other accepted norms involving asymmetric tides, catchment runoff, Trevallyn Dam and the influence of the North Esk have been challenged throughout this thesis.

This chapter provides a general discussion and conclusions from the study and synthesises the material into a coherent whole. The following sections summarise each chapter, state whether proposed hypotheses were met and discuss the implications of the findings (Table 7.1). The limitations of the study, management implications and opportunities for future research are also outlined.

Discussion

Chapter 2

The concept of regime or morphological equilibrium is central to the structure of the thesis (Fig. 1.17). In Chapter 2 the processes acting to create regime are analysed as the

Tamar system rapidly recovered from an anthropogenically created state of *over* equilibrium. The concept of equilibrium in the Tamar (BMT_WBM, 2008; Foster et al., 1986) was found to be somewhat of a myth; instead a dynamic equilibrium best described the recovered state, as forcing parameters rarely remained stable. Velocity asymmetry was found to increase as regime was approached. This suggested that artificial removal of flood-biased asymmetric tides would be counterproductive as an accretion reduction measure. At regime a constant feedback loop exists between slumping of the banks -> scouring of the channel -> accretion on the banks. This loop is driven by the competing influences of M4 and M6 harmonics. It has implications for the efficacy of the silt raking process in the Tamar and possibly for dredging in other estuaries. Restricting silt raking to the channel may be beneficial. This could be applied for one season as an exercise in adaptive management. Anecdotal evidence suggests that during high flow events most scour occurs in the channel and raking there fulfils the PIANC (2011) prerequisite of *working with nature* (for success). Similar studies of systems regaining the original equilibrium following dredging, raking or flood-scouring were not found in the literature and as such this study fills an important knowledge gap.

Chapter 3

"*All models are wrong but some are useful*" (Box and Draper, 1987).

The model developed in Chapter 3 (FORM) assumes equilibrium and logically follows the investigation of the processes that create morphological equilibrium described in Chapter 2. The model, FORM, accurately predicted the contemporary state of the upper Tamar (see linear regressions, Table 3.2), the Petitcodiac (Fig. 3.8) and Avon Rivers (Fig. 5.6) and accurately described the original regimes of the Tamar in 1806 and the changed regimes of the Petitcodiac from 1968 to 2004. The model extends the applicability of other regime models to coastal-plain estuaries with multiple tributaries (e.g. Avon Fig. 5.6) and multiple intertidal storages (e.g. Tamar Fig. 3.9). The concept of longitudinal bathymetric migration following a change to one or more forcing parameters is embodied in the application of FORM but was not previously described in the literature. The Petitcodiac is a classic example of longitudinal bathymetric migration following a change in forcing parameters (Fig. 3.6). This concept also proved useful in a qualitative sense, for analysing changes in La Rance (Fig. 5.8) which is a ria, rather than a coastal plain estuary.

Chapter 4

A consistent theme of past recommendations for remediation of the upper Tamar estuary is the installation of a Total Exclusion Barrage (TEB) as a ‘solution’ to the silt accretion issue. Foster et al. (1986) calculated the tidal prism ramifications for a TEB near Freshwater Point (Fig. 4.1) inferring that the idea was flawed due to the downstream reduction of the tidal prism. In many parts of the world, TEBs have existed for over a hundred years; Le Châtelier for instance was built in 1832, and the morphological ramifications of these structures are now becoming apparent. TEBs are a simple application of FORM in which the bathymetry migrates from the head of the estuary to the barrage (the migrated bathymetry may be longitudinally compressed or elongated; examples are cited in Chapter 5). In Chapter 4, FORM is applied to five putative TEBs in the Tamar River estuary to ascertain the morphological impacts and likely ecological consequences. It was concluded that no benefit was to be gained from installation of any of the TEBs. Moreover, evidence from existing installations was that the morphological and ecological impacts were generally negative.

Chapter 5

Mitigation of sea-level rise was not a design criterion for any of the barrage proposals discussed in Chapter 4. Mitigation of sea-level rise due to climate change is an important and emerging study area and is discussed in Chapter 5. This work was the basis of a paper presented at the ECSA55 conference in London (September 2015). The concept of bathymetric migration introduced in Chapter 3 was used to analyse the morphological trade-offs of four international examples of TEBs and to assess the trade-offs against the sea-level rise mitigation potential of each TEB. Sea-level rise has important implications for the city of Launceston at the head of the Tamar estuary. The city is reliant on flood defence infrastructure (levee banks and flood gates) for protection against sea-level rise. Approximately 4 km^2 (Davis and Kidd, 2012) of former tidal flats are now either urbanised or under intensive agriculture and up to 600 mm below MHWL. With sea-levels rising at ~3 $mm.yr^{-1}$ or more (Fig. 1.5), the rising water table poses a threat to low lying infrastructure (further described in Appendix F). The issue of sea-level rise was not a major topic in this thesis but is recommended as a priority for future research (see **Recommendations for further research**).

Chapter 6

This chapter discusses potential mitigation strategies based on the understanding of morphological processes developed in this study. Morphological rejuvenation of the upper

Tamar River estuary is hampered by urban development on the old tidal flats of Inveresk and Invermay and the intensive agriculture and infilling of the Glebe (Fig 1.13). The degradation is typical of many estuaries worldwide; removal of the root-causes is not practicable and hysteresis is likely to occur, i.e., reversion to the previous state may not be possible. Hence mitigating strategies are required and in Chapter 6 the modelling of some potential remediation projects is described. This includes the removal of levees (where possible) as well as novel approaches, such as the creation of tidal lakes and re-instatement of old meanders. Some of these approaches may be applicable to other estuaries in Australia and other countries.

In the upper Tamar, the flow diversion created by the Trevallyn Dam creates a particular problem for the Yacht Basin (Fig. 6.7). A mitigating project involving redirection of the water flowing out of the hydroelectric power station at the Tailrace to the Yacht Basin seems prospective but requires demonstration of a favourable benefit to cost ratio. Similar problems in other estuaries must be considered on their merits.

Some of the remediation strategies investigated in this study are now gaining some political traction. During the 2016 Australian Federal election campaign one political party supported the general findings of this study (www.examiner.com.au/story/3998757/**greens-push-tamar-plan**/ accessed 29th June 2016), the policy being:

- Cessation of raking
- $1 million in funding for Hydro Tasmania to investigate redirecting outflows from the Trevallyn power station back to the mouth of the South Esk
- Opposition to the proposed Tamar Lake project which would see a barrage installed south of the Bell Bay Port
- Investigating restoration of floodplain channels
- Upgrade of sewerage infrastructure to address the issue of sewage and stormwater discharge into the upper estuary

It remains to be seen whether these strategies are pursued but this thesis does provide some confidence that a new management paradigm for the upper Tamar River estuary, based on an understanding of estuarine processes, could be achieved.

The general hypothesis addressed in this thesis is that morphological degradation of estuaries generally results from a lack of flow and that increasing flow will in some part ameliorate the degradation. The effects from a large flood in the South Esk River of June 2016 (Fig. 1.14) provide a fitting footnote. The flood peaked at 2375.8 m^3s^{-1} and was followed by a smaller flood peaking at 280 m^3s^{-1}. The floods removed >182,000 m^3 of silt from the Yacht Basin with only a brief period of silt raking. The plot shows how the previous seasons of raking in 2013, 2014 and 2015 became increasingly ineffective due to lack of high flow events. The results overall confirm the hypothesis that any permanent solution must involve higher flows.

Table 7.1 Summary of aims, hypotheses, outcomes and conclusions for each chapter

Chapter & Title	Aim	Hypothesis	Outcome	Conclusion
Chapter Two – Equilibrium imbalance due to sediment raking influences M2 tidal constituent, M4 and M6 harmonics, tidal asymmetry and net sediment flux	To determine the reaction of M2, M4 and M6 tidal constituents to a forced change in equilibrium status and predict the interaction at equilibrium when net sediment flux is zero	That post raking; (a) the M4-induced asymmetry (type-1) dominates any M6-induced asymmetry (type-2), (b) M4 is affected by the removal and reformation of tidal flats; (c) M6 increases channel depth as equilibrium is approached; (d) changes to θ_{M6} and θ_{M4} are subtle; θ_{M6} increases towards its angle of greatest influence whereas θ_{M4} increases away from its angle of greatest influence and (e) that at equilibrium the influences of M4 and M6 are 'equal and opposite'.	(a) Hypothesis is confirmed. (b) Confirmed, M4 correlated with increased accretion on tidal banks (c) M6 was found to contribute to high velocities before ebb which scoured the channel and kept sediment in suspension (d) Confirmed but change is subtle (e) M4 and M6 generate a process loop at equilibrium whereby the channel is scoured, the banks accrete and eventually slump into the channel	1. Efficacy of the raking process could be enhanced by concentrating on the channel rather than tidal flats. 2. Anthropogenic reduction or removal of asymmetric tides is counterproductive 3. Equilibrium is best described as dynamic equilibrium due to the ever changing forcing parameters. 4. Tidal velocity asymmetry maximises at equilibrium 5. At equilibrium a feedback loop is established between accretion and slumping of the banks and scouring of the channel
Chapter Three – A First-Order Morphological Response Model (FORM) for predicting hydrologically induced bathymetric change in Coastal-plain Estuaries	To develop a simple regime model applicable in coastal plain estuaries for modelling the bathymetry according to certain forcing parameters	(a) that the geometry of an estuary could be accurately modelled (Figure 3.1, regime state 1) by combining regime theory with a site-specific tidal prism equation expressed as a function of distance from the head and a width equation (b) the model could be used to predict the bathymetric outcome (width and tidal prism) (Figure 3.1, regime state 2) emanating from an anthropogenic adjustment of the	(a) linear regression of modelled results show a match with present conditions (b) FORM successfully reconstructed the 1806 and 1890 widths. The volume of sediment accreted since 1806 was modelled and found to be within the accepted range (10-15*$10^6 m^3$); the inference being that that 1806 model is accurate, and the	The model developed (FORM) proved to be accurate when modelling the Petitcodiac and Tamar River systems and should have universal applicability to coastal-plain estuaries

		tidal prism	second hypothesis is confirmed.	
Chapter Four – A scenario-based approach to evaluating potential environmental outcomes following a tidal barrage installation	To assess the different ecological and morphological impacts of five putative total exclusion barrages in the Tamar River estuary	that the impacts of a barrage on estuarine hydrology, morphology and ecology in the Tamar River estuary would vary with the distance of the installation from the mouth	Installation of a TEB would result in adverse environmental impacts and declining ecosystem services throughout the estuary, and that these worsen for barrages closer to the coast.	Rehabilitation must address the major stressors which have been previously identified as anthropogenic changes to riverine inflows and tidal flushing (Davis and Kidd 2012). The analysis provides a starting point for a wider sustainability analysis in which environmental, social and economic objectives should be considered.
Chapter Five – Total exclusion barrages as sea-level rise mitigators: The geomorphological trade-offs for new installations	Consider whether the morphological changes evident in our examples are consistent with the predictions of FORM To assess whether the benefits of mitigating against sea-level rise would be out-weighed by the trade-offs associated with a total exclusion barrage in the Tamar River.	that the existing structures provide differing levels of protection and that none provide justification for a TEB in the Tamar River estuary.	Using four examples of existing TEB installations, it was shown that the morphological impacts, which were severe, can be effectively modelled using FORM (where appropriate) and that this provides a useful tool to predict the outcomes of new TEB installations In a qualitative sense, bathymetric migration was useful in analysing the changes which have occurred in La Rance, which is a a ria (as distinct from a coastal-plain estuary)	TEBs provide little mitigation of sea-level rise, although surge protection barrages may be useful.as is providing accommodation space. Despite this increasing level of complexity, none of the study sites provide evidence to support the installation of a TEB to mitigate SLR in the Tamar River estuary.
Chapter Six – Bathymetric rejuvenation strategies for morphologically degraded estuaries	To identify possible sustainable remediation strategies for bathymetric rejuvenation in the Tamar River estuary, for which the probability of success is high	The aim was to identify those strategies having a high probability of success, whilst identifying trade-offs of other proposals which do not address the known stressors. Implications for asymmetrical tides, existing storages and other ecosystem services are considered.	The modelling shows that sustainable remediation strategies in the study area are theoretically possible by removing or mitigating the stressors causing the problem. Strategies providing positive benefits are generally applicable to similarly degraded estuaries elsewhere; i.e. the removal of barriers to water and sediment movement, will encourage maximum accommodation space and	This study highlighted the trade-offs in remediation activities which do not address the initial stressors. In this example they acted to exacerbate the silt accretion problem. Modelled projects showing potential could progress confidently under adaptive management, but where large capital outlays are involved,

	increase the tidal prism and cross-sectional area	confirmation of predictions through numerical modelling of potential strategies, is recommended as a precursor to implementation

Limitations of the study

Within this thesis assumptions are made which limit the applicability of the results to some extent. For instance, assumptions made by FORM limit its application to coastal-plain estuaries or to sections of other estuaries confined by erodible sediments. The accuracy of calculations is limited by the physical variation in actual estuarine widths and the accuracy of the measurement itself. Results have been statistically shown to be useful and sufficiently accurate, having been generated by a scientific process superior to what is known in the vernacular as ‘back of the envelope calculations’. I prefer the term ‘order of magnitude calculation’ which was used in Chapter 5 with acceptable results.

Ideally a study which monitored change in an estuary would include a control (i.e. reference) estuary that was devoid of anthropogenic influences. This proved impossible as no other estuary of similar length, tidal range etc. exists anywhere and certainly not within practical distance. Duplication of bathymetric surveys, tide-gauge and velocity measurements were beyond the budget of this study. Budgetary constraints restricted tidal measurements to one site on the upper Tamar. However, the ensuring dataset, combined with tidal data and bathymetric surveys conducted by the Launceston Flood Authority, provided sufficient data to investigate the research questions posed.

Recommendations for further research

The implications and mitigation of sea-level rise is a pressing issue worldwide and especially for the city of Launceston. The issue gained greater prominence during the course of this study, with recent trends indicating an annual increase of ~3-5 mm, up from ~1 mm over the last one hundred years. Time did not permit a more thorough investigation into this matter, but it is flagged as a priority for future research.

The discharge of raw and partly treated sewage into the Tamar and North Esk Rivers is a major water quality issue which was not addressed in this thesis. However, it is also flagged as a priority for future research.

For the purposes of this thesis, FORM was run on a spreadsheet with resolution limited to 100 metres of linear spacing along the estuary. A finer resolution could be attained using computer code which allowed for point sources and channel widths to be modelled at the metre scale. This would also allow longer coastal-plain estuaries to be modelled in manageable longitudinal sections.

Future research could be co-ordinated through the Co-operative Research Centres Program (CRC) which "is a competitive, merit based grant programme that supports industry-led and outcome-focussed collaborative research partnerships between industry, researchers and the community" (https://www.business.gov.au/assistance/cooperative-research-centres-programme accessed October 2016). Grants are either short term (3 years) or long term (10 years) and are industry-led collaborations. A CRC would partly satisfy the main recommendation of the Legislative Council Tamar Estuary and Esk Rivers Select Committee (http://www.parliament.tas.gov.au/ctee/Council/Archived/Reports/mte.rep.091028.rpf.tw.001.a.pdf accessed October 2016) (see Table 1.3); that management of the system be brought under the control of a single statutory authority. Although not a statutory authority, a CRC would serve to focus the efforts of the various organisations with an interest in the Tamar estuary.

Ecologically focussed research topics could include developing methods for sustainable rice grass eradication and the assessment of rehabilitated tidal flats and salt marshes as feeding and spawning grounds for native fish species.

Management implications

The findings of this study provide a clear policy direction for future interventions in the upper Tamar estuary whilst highlighting strategies and management actions to be avoided. PIANC (2011) summarised this succinctly:-

"*Act with nature for success; act against nature for failure*".

This maxim can be applied to any degraded estuary. Locally, the attitudes of both the public and management authorities towards tidal flats are that they are unsightly and unhealthy intrusions in the upper estuary which should be used for agriculture where possible and removed if not. This attitude is understandable given the contamination and poor ecological health of the silt but must change to one which recognises the ecological worth (in terms of spawning areas for fish and feeding areas for both fish and birds) and the important hydro-dynamic and morphological roles which tidal flats play. Improving water quality by updating sewage treatment with a more appropriate point of discharge would help with changing the public perception. Clean unpolluted intertidal areas may also have some monetary value in terms of eco-tourism.

Notwithstanding the past efforts of many well intended community groups and with the above maxim in mind, future management action should focus on removal of barriers to water and sediment flows and maximising the tidal prism as much as possible. Sea-level rise looms as the great unknown in terms of forcing factor, but irreversible rises in the order of meters are predicted over the coming centuries https://www.ipcc.ch/pdf/unfccc/cop19/3_gregory13sbsta.pdf (accessed 4/3/2017). In round figures, the recently completed flood levees have an elevation of ~5 m AHD which is ~3 m above present day MHWS. A combination of SLR, king tides and flooding events could result in the failure of flood levees within the next 100 years or so. Unlike episodic flooding, sea-level rise is predictable and from a management point of view, a long lead-in time is available for contingency planning. Strategies for dealing with sea-level rise are not incongruous with the silt reducing strategies developed in this thesis. The ideal SLR adaptation is to provide maximum accommodation space which allows the estuarine bathymetry to rise in unison with sea-level (see Chapter 5). Similarly, whether sea-levels rise or not, maximum accommodation space induces maximum tidal prism by increasing intertidal storage volumes, and hence reduces silt accretion within the estuarine channel (see Chapter 6). To achieve this objective, a management strategy should include the following elements:-

- A planning policy which precludes development below a certain elevation. For immediate silt reduction, suggest 3 m AHD; for long term SLR, suggest 10 m AHD
- A planning policy which encourages retreat from areas mentioned above
- Removal of tidal levees and rehabilitation of non-urbanised intertidal zones
- Removal of sluice gates in the tidal marshes of the North Esk intertidal zone
- A feasibility study into the strategies developed in Chapter 6

In the past many community groups have attempted to instigate rejuvenation projects in the upper Tamar the most recent being the Upper Tamar Rejuvenation Project (UTRP) of which the author was a member. Such organisations require considerable personal commitment and ultimately little is achieved. A more authoritative organisation is required with the necessary approval to instigate meaningful change as recommended by the Legislative Select Committee on the Tamar and Esk Rivers (http://catalogue.nla.gov.au/Record/4791739 accessed 4/3/2017). A CRC meets most of the criteria and is suggested as a compromise solution.

This recommendation and others within this thesis provide on-going opportunities for the AMC and/or IMAS to:-

- Co-ordinate the establishment of a CRC
- Develop estuarine science courses
- Maintain on-going tide gauge(s); possible permanent buoy for velocities, water quality, salinity and turbidity
- Create a portal for a Tamar estuary information database

Ideally the CRC would make recommendations to support implementation of a sustainable rehabilitation plan for the Tamar based on the understanding of estuarine processes, cost-benefit analyses and community aspirations. In the short term, a trial raking program concentrated in the channel would enable the efficacy of the raking program to be assessed.

Other roles of the CRC could include:-

- Planning and development of policy for the renewal of sewerage infrastructure and sewage effluent discharge into the Tamar and other estuaries
- Setting ambitious but achievable targets for water quality
- Development of community awareness programs of Tamar issues and solutions based on an understanding of estuarine processes
- Co-ordinating with town planners on estuarine issues, including the implications of sea-level rise for tidal flat development & the potential for eco-tourism initiatives based on upper Tamar ecosystems.

Conclusions

Various anthropogenic influences contribute to the present lack of flow in the upper Tamar estuary; canalisation, redirection, realignment, infill, diversion and the irreversibility of these means that hysteresis is present in the system. This thesis considered the processes which are generated from those interventions and hypothesised that mitigating strategies could overcome hysteresis to attain an improved equilibrium position despite the persistence of flood-biased asymmetrical tides. A simple but accurate regime model was developed which confirmed the hypothesis in the upper Tamar River estuary in Tasmania, the Petitcodiac River estuary in New Brunswick, the Avon River estuary in Nova Scotia, La Rance estuary in France, and Tees River estuary in UK. Successful remediation projects were cited from the US as were numerous modelled and actual examples of flow reduction causing morphological problems in Australia, Asia, Europe, UK and North America.

This thesis adds to the body of knowledge on estuarine restoration and informs the management of estuaries worldwide. At the outset this research question seemed complex and had been in the too-hard-basket for over 200 years, but as with many research projects, the most elegant solutions are often the simplest solutions.

APPENDIX A:

IDENTIFYING MAJOR STRESSORS: THE ESSENTIAL PRECURSOR TO RESTORING CULTURAL ECOSYSTEM SERVICES IN A DEGRADED ESTUARY (Davis and Kidd, 2012)

Abstract

World-wide estuaries have been subject to multiple and escalating anthropogenic impacts which have resulted in the loss of many ecosystem goods and services including: commercial activities; navigation and marine transportation; recreational and landscape values; flood control and biodiversity support. An example of these losses is provided in an urban-industrial region of an estuary in northern Tasmania, Australia, where excessive silt deposition has resulted in almost complete loss of the channel at low tide. The causes of siltation have long been attributed to poor watershed management and high concentrations of flocculated and suspended sediments transported upstream by asymmetrical tides. However, historical analysis of anthropogenic changes in estuarine and riverine processes revealed different stressors. These included the decrease in the tidal prism and hence regime equilibrium, brought about by channel infilling and draining of tidal wetlands to create dry land for urban and agricultural uses, and the reduction and re-direction of freshwater inflows for the generation of hydroelectricity. Watershed sediment loads exerted a relatively minor role in the estuarine equilibrium, which is solely dependent on tidal flows and river discharges for maintenance of stable cross-sectional areas. Sustainable remediation measures include increasing the tidal prism through the restoration of dynamic river flows and reconnection and restoration of tidal wetlands. However, the former will not be achievable without changes in major provisioning services, particularly the use of water to generate hydroelectricity. This study emphasises the importance of identifying stressors as the basis for examining the potential to reduce the trade-offs between the multiple ecosystem services provided by an estuary and its tributaries, particularly between provisioning and cultural ecosystem services, within a rehabilitation context.

Keywords: tidal prism, dynamic flow regime, tidal wetlands, hydroelectricity

Introduction

Globally, estuaries are focal areas for much human activity but also represent the most anthropogenically degraded habitats on earth, being subject to multiple and escalating impacts (Baird, 2005; Lotze et al., 2006). In Australia, as elsewhere, estuaries were the principal sites of European settlement due to multiple benefits, including the ease of shipping access, availability of freshwater and presence of productive alluvial lands for agriculture (Edgar et al., 2000). The Tamar River estuary, in northern Tasmania (Fig. 1), was one of the earliest sites of European settlement in Australia, with initial settlement in the lower reaches at Yorktown in 1804, followed by establishment further upstream of the nation's third town, Launceston, in 1806, which now supports a regional population of 90,000 http://www.launceston.tas.gov.au/lcc/index.php?c=85 Accessed 9 October 2011).

A management plan was developed in 2000 in recognition of the considerable pressure placed on the natural values of the estuary through intensive use and development within the watershed (www.nrmnorth.org.au accessed 9 October 2011). Continuing community concern about the poor state of the Tamar River estuary and Esk Rivers resulted in the establishment of a Tasmanian parliamentary committee to investigate the issues, particularly sedimentation and flooding. It recommended the establishment of a single statutory authority to manage the waterways (www.parliament.tas.gov.au. accessed 9 October 2011).

The Tamar River estuary and its tributaries, the North and South Esk Rivers, provide multiple services and benefits to the surrounding population. The major provisioning service is the supply of water for hydro-electricity provided by the Trevallyn Dam on the South Esk River (Fig.1). The power station generates $30 million annually but the environmental impact has been a 95% reduction from 30 m^3sec^{-1} to 1.5 m^3sec^{-1} in base flow to the upper estuary through the Cataract Gorge. An additional 20 m^3sec^{-1} is supplied from another hydroelectric scheme (the Poatina Scheme) taking the total base discharge from the station to 50 m^3sec^{-1}. This enters the estuary at the Tailrace (Fig 1). Water is also extracted from the tributaries for domestic water supply, food production and some industrial purposes. Waste disposal is a major regulating service with the estuary receiving treated sewage and storm water, irrigation outflows and industrial waste discharge generated within the watershed.

The Tamar River has always been an important shipping route, although the port of Launceston has been relocated twice from the original site at the confluence with the North Esk River to the deep water of Bell Bay, near the mouth. Service to shipping is a multi-million dollar business with a ship lift facility used for large vessels and smaller slipways catering for fishing and recreational vessels. Recreational activities such as sailing and rowing have traditionally had a strong following, tourist boats ply the upper reaches and a floating marina was established near the mouth of the North Esk in the 1990s (Figs. 1 and 2).

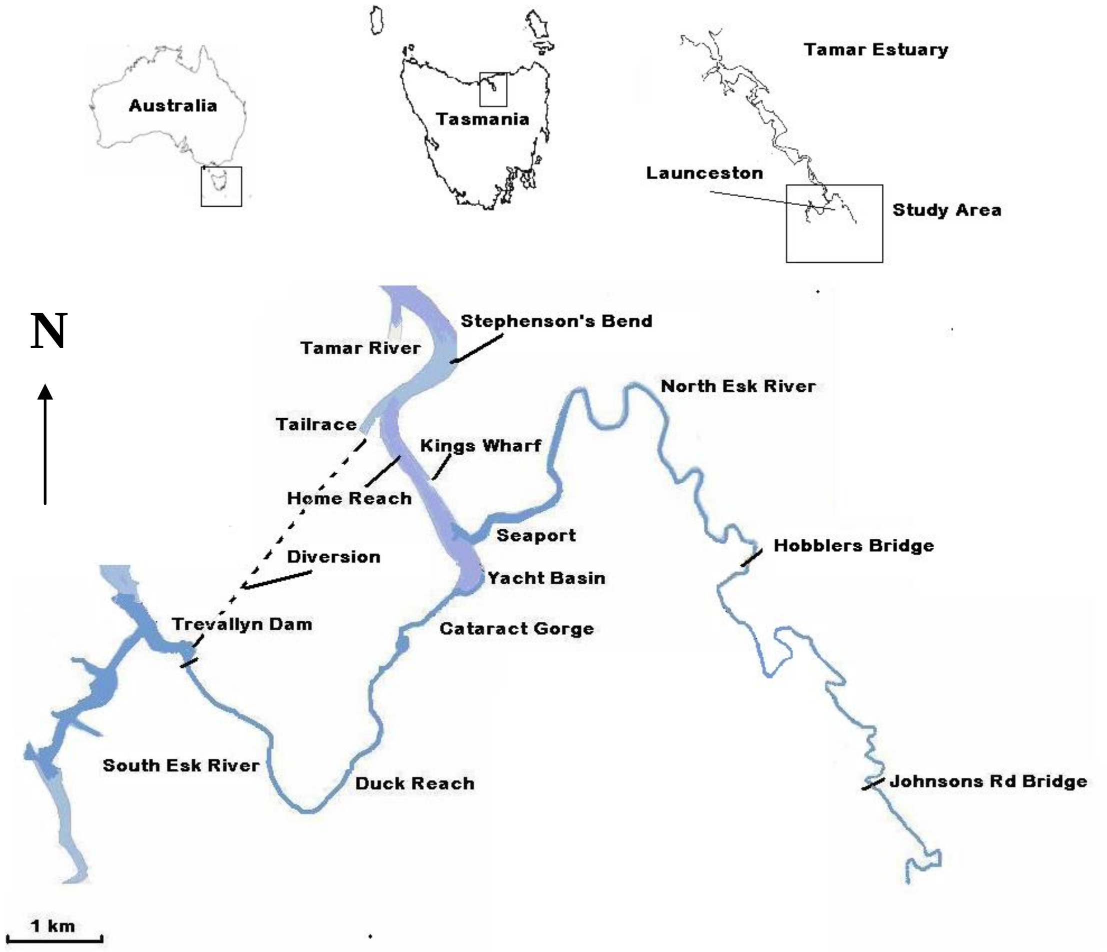
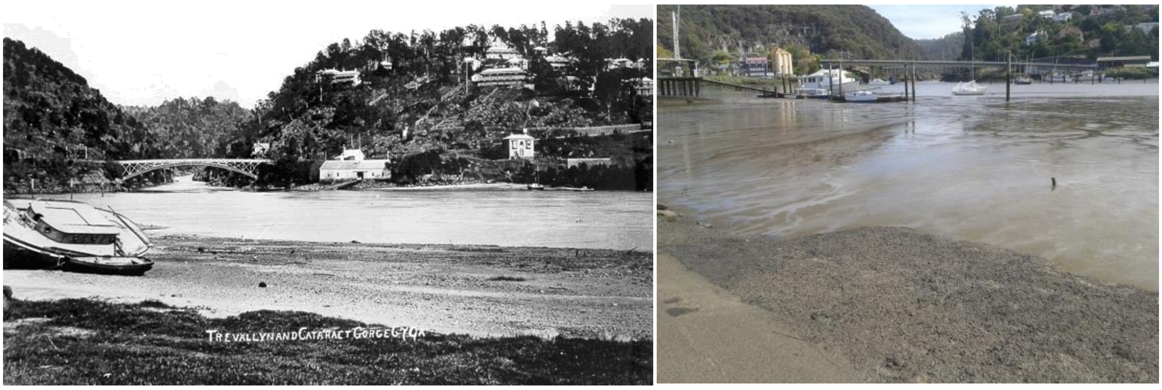


Figure 1. Location of the Tamar Estuary and the North and South Esk Rivers in Northern Tasmania, Australia

Fig. 2 Seaport marina on the North Esk River 2011 showing loss of amenity due to excessive silt deposition

Deposition of silt, resulting in a much reduced channel section in the upper estuary, has been considered a problem for over 100 years (Figs. 2 and 3). Dredging was used from the late 1800s onwards to keep shipping channels open, but increasing costs and disposal problems have recently curtailed this practice. Cessation of dredging, and associated increase in silt deposition has resulted in the loss of many cultural ecosystem benefits and values. The mooring of keel boats and sailing is no longer possible, rowers become stranded on the mud and sections of the marina are rendered unusable (Fig 2). Amongst the Launceston community the extensive mudflats are considered unsightly, representing a considerable loss of aesthetic amenity and landscape values. Extensive silt deposition is also perceived to indicate elevated levels of contaminants, although this is not necessarily true (BMT_WBM, 2008).



a b

Fig. 3 (a) View across the Yacht Basin to the Cataract Gorge and South Esk River at low tide c1900 showing coarse sandy beaches, a fresh water inflow of approximately 30 m^3sec^{-1} and >200m wide water body; (b) view at low tide across the Yacht Basin in 2011 showing excessive silt deposition and greatly reduced channel width.

The need to restore socially-valued ecosystem services to the upper estuary has been clearly articulated by the local community (http://www.launceston.tas.gov.au/upfiles/lcc/cont/environment_and_waste/pdfs/river_management/siltation study.pdf. accessed 9 October 2011). However, much of the focus has been on the removal of silt by dredging. This approach addresses the symptom of the problem, rather than the cause. We sought to determine the causal factors as the basis for developing a sustainable rehabilitation strategy. Furthermore, the knowledge that landscapes produce multiple ecosystem services which interact in complex and dynamic ways (Bennett et al., 2009; Kremen and Ostfeld, 2005) meant that the potential to maximise synergies and reduce trade-offs between multiple ecosystem services should be considered as part of a rehabilitation strategy. We sought to identify the major stressors as the essential first step in this process.

Site Description

The Tamar River estuary comprises a watershed of approximately 10000 km^2 with a length of 70km from the confluence of the two main tributaries, the North Esk and South Esk Rivers, to the mouth at Bass Strait (Fig. 1) (www.nrmnorth.org.au Accessed 9 October 2011). The climate of the region is cool temperate with an average annual rainfall of 680 mm (http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av? Accessed 9 October 2011). The estuary, classified as a mesotidal drowned river valley by Edgar et al. (2000) was formed by sea level rise over the last 13,000 years. Australian drowned river valleys, such as the Tamar, are considered to be geomorphologically similar to typical North American and West European systems (Eyre, 1998). Sediment inputs from the North Esk and South Esk Rivers flocculate at the saltwater boundary. When river flows are low, during droughts or dry summers, flocculated sediments are transported upstream on asymmetrical tides, resulting in deposition in the upper reaches of the estuary (Foster et al., 1986) (Figs. 2, 3b).

The upper Tamar River estuary, which was the focus of this study, generally accords with Weinstein (2007) urban-industrial definition, although the important societal values of recreation, tourism and landscape aesthetics still exist. The middle and lower reaches are more closely aligned with Weinstein's conservation definition, with minimal human shoreline density and few human extractive uses.

Methods

Our approach was to determine whether the excessive siltation in the upper Tamar River estuary was attributable to anthropogenic changes within the estuary, causing a loss of tidal prism rather than other processes, such as flocculation, asymmetrical tides and watershed sediment loads, all of which had been implicated in previous studies.

Historical Analysis of Changes in Hydrology and Land Use

A timeline of anthropogenic changes, including loss of tidal wetlands, land infill, channel re-direction and flow alteration, was constructed from a variety of sources (Table 1). These included the analysis of historical charts and maps sourced from the regional library and old photos available online from state and national libraries. Articles from the local newspaper (The Examiner) were also used. Many unpublished reports produced by studies commissioned to address declining estuarine amenity, particularly silt deposition, were reviewed, including those commissioned by the Launceston City Council (LCC), Hydro Tasmania, Port of Launceston Authority and others.

Tidal Prism Calculations

Quantification of the historical changes occurring within the estuary and rivers was based on the estuarine equilibrium model O'Brien (1966), subsequently modified by BMT_WBM (2008) who used numerical models of a range of inlet entrance channels, from minor creeks to large rivers, to develop the following equilibrium relationship:

$$\boldsymbol{A = 3.1 \times 10^{-3} P^{0.81}}$$

where A is cross-sectional area below half tide (m^2), and P is Tidal Prism (m^3). This equation indicates that any action which modifies the tidal prism will produce a response in the cross-sectional area. The equation was used to establish the cross-sectional area at equilibrium for a known tidal prism and vice versa. Where appropriate, the present and historical tidal prisms were calculated from the product of the half tide surface areas upstream of the section and the known tidal range.

Table 1. Timeline of events affecting tidal and fresh water flows in the upper Tamar River estuary since 1806.

Date	Event	Reference/Source
1806	Town of Launceston settled at confluence of North and South Esk Rivers	LCC (2011)
1830	River survey conducted showing maximum low tide depths	Fig. 6
1857	St Patrick's River weir constructed, diverting 0.347 cumecs to town water supply. Small TP loss	http://engineersaustralia.org.au/. Accessed 9 October 2011
c1890's - 2010	Dredging North Esk mouth causes tidal regime change and leads to sedimentation in the southern side of the river channel	Fig. 7b
c1900 - 2011	Draining tidal wetlands results in tidal prism losses of 760,000m^3	Fig. 7a-c
1920's	In-fill at Royal Park results in tidal prism loss of 325,000m^3	Figure 7c
1920's	Redirection of the North Esk alters regime in the Yacht Basin and deposition results. Stable cross-sectional area reduced to 280m^2	Figures 2, 7c
1955	Trevallyn Dam built. South Esk discharge reduced from 1,296,000m^3 per tidal cycle to 64,800 m^3 per tidal cycle	(Foster et al., 1986)

This approach was similar to that of (Hood, 2002, 2004) who noted that an allometric approach to tidal channel hydraulic geometry is useful because tidal channel surface area and perimeter can be measured from aerial photographs or maps to indirectly evaluate the effects of the tidal prism. This avoids the need for more costly measurements of channel depth or cross-sectional area and is important where historical cross-sectional information is not available.

A tidal range of 3.25m was used to provide an estimate of the tidal prism as tides range from approximately 2.34m at the mouth, 3.25m at Launceston and nearly 4m in the upper North Esk (BMT_WBM, 2008). Fresh water discharges over a complete tidal cycle (12hrs) were used as a comparison to tidal prism where necessary and are referred to as tidal prism equivalent. River lengths were calculated using imagery available from Google Earth. Calculations were based on the cross-sections provided by the Launceston City Council (LCC) (Fig. 4). Area calculations were made using FreeMapTools (http://www.freemaptools.com/area-calculator.htm. accessed 9 October 2011).

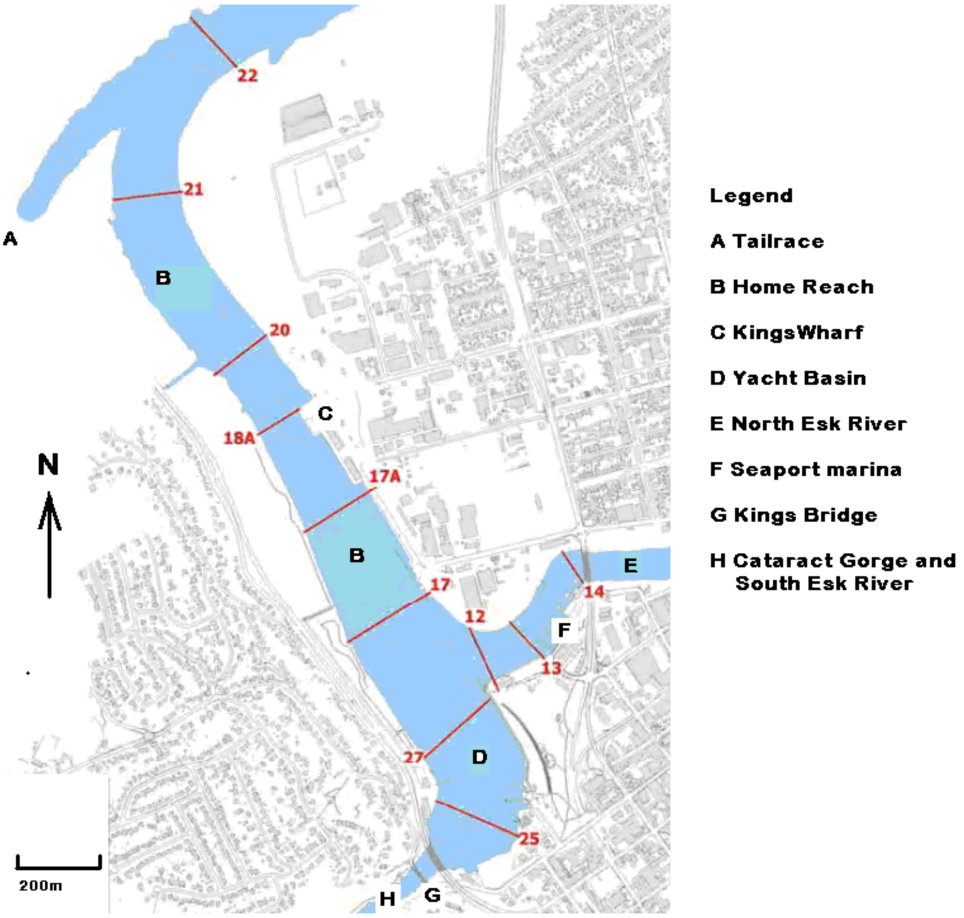


Figure 4. Launceston City Council silt monitoring sites on the upper Tamar River estuary.

Losses in the tidal prism were assessed by comparing the difference of the existing and historical tidal prisms at Kings Wharf, with the total losses from known anthropogenic changes since 1830. The historic cross-sectional area at Kings Wharf in 1830 was derived from the tidal range, the width at high tide (Fig 5), and the depth and width at low tide (Fig 6).

Fig. 5 1832 map with tidal wetlands (swamps) marked as stippled regions, mainly in the upper third. An insert (lower right) shows the historical tidal boundary on the North Esk River at (A) and the current tidal boundary at (B): Source Launceston Regional Library.

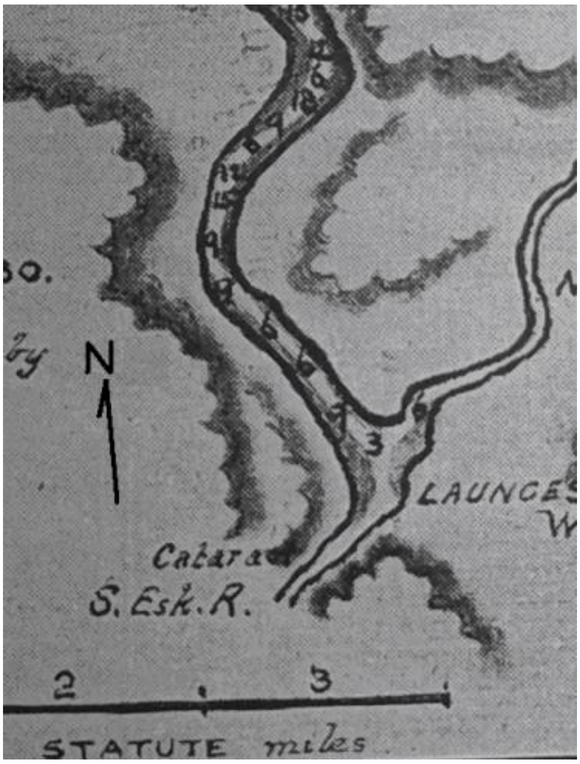


Figure 6. Magnified section of a survey chart from 1830 showing channel depths (ft). Source: The Examiner 31/3/1930.

Results

Identification of Stressors

Reduction in Freshwater Inflows

The first major reduction in freshwater discharge to the estuary occurred in 1857, when a diversion dam was built on the St Patrick's River, a tributary of the North Esk River, to provide a water supply to the town. A weir replaced the dam in 1888, and this was upgraded in 2008 to provide 30 mega-litres/day (0.347 m^3sec^{-1} (http://engineersaustralia.org.au/. accessed 9 October 2011). Some of this water returns to the estuary as stormwater and treated sewage at Section 22 (Fig. 4). A further 15-25% reduction in inflows to North Esk River, and ultimately the estuary, during dry periods, has recently been attributed to an increase in plantation forestry within the watershed (Peel et al., 2003).

The largest reduction in riverine inflow occurred in 1955 with the construction of the Trevallyn Dam. Previously, a power station built on the South Esk River at Duck Reach, in 1895, provided the first successful hydroelectric power for electric street lighting in Australasia (Pierce, 2007). It was decommissioned in 1955, when the building of the

Trevallyn Dam further upstream diverted river water away from the confluence of the South Esk River and the upper Tamar River estuary through the Trevallyn Power Station (Fig.1). Before 1955, the base-flow was 30 m^3s^{-1}, but post 1955 this was reduced to a legislative requirement of 0.42 m^3s^{-1}. Hydro Tasmania recently voluntarily increased this to 1.5 m^3s^{-1} (http://www.launceston.tas.gov.au/upfiles/lcc/cont/environment_and_waste/pdfs/river_management/silt_study.pdf.; accessed 9 October 2011). The remainder now discharges through Trevallyn Power Station and enters the estuary at the Tailrace, between Sections 21 and 22, downstream of the area of interest (Fig. 4). An additional 20 m^3sec^{-1} from an inter-basin transfer (the Poatina Scheme) now also discharges through the power station. The 28.5 m^3s^{-1} reduction equates to a discharge loss, or tidal prism equivalent, of 1,231,200 m^3 per tidal cycle.

Channel Aggradation

Migration of the tidal boundary occurs by aggradation when the coarse fluvial bed load of the river meets the quiescent tidal water body (Strahler, 1973). Conceptually, the effect of this loss is for the bed profile to move downstream by the same distance. Comparison of the location of the current (2011) and historic (1832) tidal boundaries in the North Esk River (Fig. 5) indicated that the tidal boundary has moved downstream by an estimated 450 m (Table 2, Fig.5). Although the loss of the tidal prism at the boundary is only an estimated 10,000 m^3, the loss to whole North Esk River system is 165,000 m^3. Each cubic metre of fluvial deposit at the boundary results in the deposition of 16.5 m^3 of fine sediments downstream in the North Esk, (excluding aggradation below low water level, which has no effect on tidal prism) and a much greater impact for the whole estuary. Aggradation in the South Esk River occurs on the upstream edge of the Trevallyn Dam impoundment and has no impact on the estuary.

Table 2. Summary of results: A Change in tidal prism at Kings Wharf between 1830 and 2011; B the sources of tidal prism loss for the same period.

Change in tidal prism at Kings Wharf		
Date	Method of calculation	**Tidal prism (m^3)**
1830	Estimated X area and O'Brien equation	**4,500,000**
2011	Known X area and O'Brien equation	**3,000,000**
	Total loss of tidal prism	**1,500,000**
Sources of tidal prism loss above Kings Wharf		
System component	Method of calculation	
North Esk wetlands drained	Known area × estimated inundation	**260,000**
North Esk aggradation	Area estimated from Fig. 5	**165,000**
Royal Park infill	Known area × known tidal range	**325,000**
Yacht Basin sedimentation	Known area × known height above low water	**135,000**
West Bank infill	Known area × known tidal range	**150,000**
Norton Wetland drained	Known area × known inundation	**500,000**
	Cumulative loss of tidal prism	**1,535,000**

Changing Land Use and Wetland Loss

Tidal wetlands on the North Esk system have either been drained or in-filled, so that none now contribute to the tidal prism. A wetland area of 1.3km^2, extending upstream from north of the 'Clergyman's Glebe' to the tidal boundary has been lost since 1832. We have conservatively estimated an average inundation of 20 cm, including dissecting channels and ground saturation, resulting in loss of tidal prism of 260,000 m^3 (Fig. 5). Downstream, tidal exchange with Norton Swamp at the river mouth (Fig. 5), contributed approximately 500,000 m^3 to the tidal prism in the upper estuary (50 cm inundation over 1 km^2). Wetland draining for urban development has eliminated this contribution.

Channel Infill and Redirection

In 1830 the depth at the mouth of the North Esk River at low tide was 3ft (Fig. 6). Subsequently, the channel was dredged to allow vessels to dock at the port further upstream. Dredging changed the channel regime so that deposition occurred on the southern side, maintaining equilibrium. By 1920 the area was infilled to form Royal Park with a large loss of river channel (Fig. 7). The loss of tidal prism calculated from the estimated reduction in area and the known tidal range was 325,000 m^3.

a

Fig. 7 a. Photo taken at low tide c1870, North and South Esk river flows meeting head on. No sedimentation evident. Source: State Library of Tasmania

b

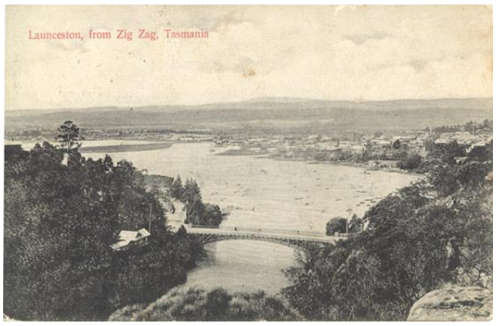


Fig. 7 b. Photo taken at low tide c1900. Norton Swamp (mid left) inundated, sediment present in the North Esk, flow redirected northward. Source: State Library of Tasmania

c

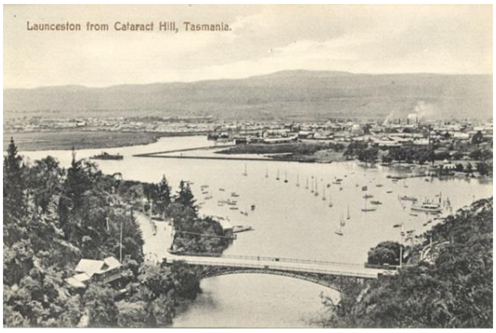


Fig. 7 c. Photo taken at high tide, Norton Swamp (mid left) drained, in-fill commenced, North Esk flow directed away from Yacht Basin. Source: State Library of Tasmania

Infilling to create Royal Park also resulted in a redirection of the discharge from the North Esk (Figs. 7a, b, c) reducing the sustainable cross-section of the upper estuary (Yacht Basin) from an estimated 700 m^2 to 280 m^2. This loss resulted in an increase in sediment deposition prior to the building of Trevallyn Dam. Increasing sedimentation in the upper estuary (Fig. 2) reduced tidal inflow, causing a further loss of the tidal prism. The present volume above low tide is estimated at 135,000 m^3, equating to the same loss of tidal prism. A small diversion channel also now exists incising a substantial meander within the upstream tidal zone of the North Esk. This diverts approximately 10% of the flow and effectively marginally shortens the river length, further decreasing the tidal prism. Infilling on the western bank of the upper estuary has resulted in an estimated tidal prism loss of 150,000 m^3.

The estimated historical tidal prism loss between 1830 and 2011 that can be ascribed to wetland loss and river flow diversion is 1,530,000 m^3 (Table 2). The change in tidal prism calculated from estimated changes in cross-sectional area over this time period is 1,500,000 m^3. Close agreement between these two volumes suggests source-response linkage to tidal prism loss.

Discussion

Identification of Stressors

Previous studies have attributed the problem of silt deposition in the upper Tamar River estuary to high sediment loads from poor upstream riparian and watershed management, flocculation of sediments at the freshwater/tidal boundary and the transport of silt upstream at low flows on asymmetrical tides (BMT_WBM, 2008; Foster et al., 1986). Our historical analysis suggests that a reduction in the tidal prism of approximately 30%, brought about by channel in-fill, channel re-direction, aggradation, and draining of tidal wetlands, has occurred since European settlement in the early 1800's. We contend that this loss of the tidal prism together with a 95% reduction in base flow to the upper Tamar estuary due to damming and diversion of a major tributary, the South Esk River, are the major stressors resulting in the present poor condition of the upper estuary. Silt deposition appears to be a symptom of the problem, rather than the cause, because it continues to occur, despite treatment by dredging for over 100 years. Silt deposition occurs within dredged areas as the system readjusts to a new regime equilibrium.

Watershed and in-stream sediment loads do cause loss of the tidal prism through aggradation at the tidal boundary. Aggradation, evident as sand deposition in the North Esk River, has caused the tidal boundary to migrate. This has caused a loss of tidal prism and hence an increase in deposition downstream, and in the upper Tamar River estuary, as the regime equilibrium is re-established with an atrophied cross-sectional area. Losses in the upper section of the tidal North Esk River are magnified downstream, so that relatively small losses become significant in the upper Tamar River estuary, as conceptualised in Fig. 8. A boundary migration rate of 2.4 m per year does not appear to be excessive given the agricultural, mining and forestry activity within the watershed. This is consistent with sediment loads in the North Esk River being classified as relatively low, on a global scale (Foster et al., 1986). The boundary migration rate prior to European settlement is not known, but was presumably less than 2.4 m/yr. As already noted, aggradation effects in the South Esk River are nullified by the Trevallyn Dam and have no effect in the upper Tamar estuary. Fine sediments are not trapped by the dam but are transferred through the power station to the estuary.

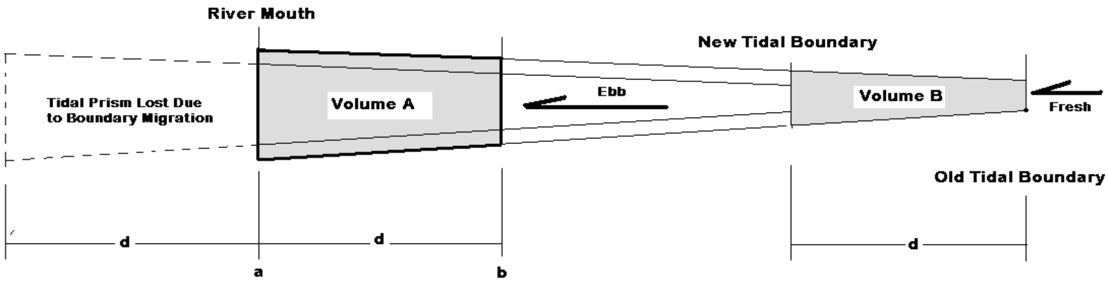


Figure 8. Conceptual model showing, in plan view, how tidal prism loss due to tidal boundary migration (Volume B) is magnified from the boundary to the mouth (Volume A). Width at the boundary is dependent on fresh water discharge only and will remain constant. Total tidal prism volume lost (A) due to migrating a distance d, is calculated as the difference in tidal prism (a) and tidal prism (b).

In the absence of floods, the Yacht Basin will diminish to a cross section sustained by only the inflow from the South Esk River, currently 1.5 m^3s^{-1}. The low tide surface width sustained by the South Esk discharge effectively provides the foundation for the tidal prism and hence the cross sectional area at half tide. The historic base-flow of 30 m^3s^{-1} provided for a much greater surface width at low tide and hence a much greater tidal prism. By calculating the respective discharges over a tidal cycle and applying that volume to the modified O'Brien equation it is evident that the sustainable cross-sectional area of the Yacht Basin (attributable to South Esk discharge) has contracted from 277 m^2 to 24 m^2. The loss of tidal prism is in part represented in the sedimentation of the western side of the Yacht Basin (section 27 to section 17) and in part by the fact that the rest of the Yacht Basin remains beyond equilibrium due to flood scouring, and this effectively masks the full effect of the discharge reduction. A study undertaken in 2005 recorded the Yacht Basin cross-section (LCC section 25) at approximately 600 m^2 (BMT_WBM, 2008). This represents a tidal prism of 3,400,000 m^3 or a discharge from the South Esk of 78 m^3s^{-1} (based on the modified

O'Brien equation). The cross section at that time was clearly affected by flood scour and was beyond the level sustainable by even the historical 30 m^3s^{-1} discharge. Accordingly, no South Esk discharge loss component is given in Table 2 as doing so would effectively be double counting of a single cause.

This discussion should not be construed as an argument to maintain the status quo. On the contrary, the succession of drought and flood conditions provides for a dynamic regime in the Yacht Basin with sediment increasing in dry periods and being scoured during floods. Modelling suggests that a base flow discharge of even 10 m^3s^{-1} from the South Esk River would reduce siltation by 50% (BMT_WBM, 2008).

Opportunities for Sustainable Restoration of Ecosystem Services by Maximising Synergies and Reducing Trade-offs

The restoration of commercial and recreational opportunities and landscape amenity to the urban-industrial section of the upper Tamar River estuary will be achieved by increasing the channel width and depth at low tide. Dredging of deposited silt will achieve this objective in the short term, but is expensive and is not sustainable in the longer term as the system remains in disequilibrium. Sustainable remediation requires re-instatement of riverine and tidal processes to support a tidal prism that is large enough to flush sediments through the upper estuary. Although a simple concept, an examination of the competing demands for both the provisioning and cultural ecosystem services provided by river and tidal waters, reveals why remediation may be difficult.

Diversion of freshwater away from the upper estuary, for the generation of hydroelectricity, provides a major provisioning service but we contend that this has occurred at the expense of cultural ecosystem services, especially recreational values and aesthetic amenity. The need to limit carbon emissions to mitigate rising global temperatures means that the generation of hydroelectricity is of increasing importance and the possibility of reducing this trade-off between services appears limited.

Sustainable restoration of the tidal prism in the Yacht Basin to a historical condition would require a discharge from the South Esk River of approximately 90 m^3s^{-1}. The historical base-flow of 30 m^3s^{-1} is insufficient because the Yacht Basin no longer benefits from the flushing effect of the North Esk River (due to river realignment). This suggests that even the costly resiting of the power station would not, in itself, completely remedy the situation. Further, the importance of naturally variable flow regimes in maintaining the ecological integrity of rivers is now well recognised (Poff et al., 1997). Accordingly, re-instatement of a naturally variable flow regime rather than a minimum flow, is a necessary requirement for river restoration (Poff et al., 2010). Strategically timed environmental flow releases from the Trevallyn Dam, combined with flood raking to mobilise biologically bonded sediments, would provide a short term improvement. However, silt deposition would still occur during low flow periods and so this strategy would require an ongoing management commitment.

Environmental flow releases in excess of 180 m^3s^{-1} would be needed to produce bed scour without raking (Foster et al., 1986). However, it is likely a compromise could be found between historical channel and present day conditions that would not require such high frequency and large magnitude discharges. The required frequency of dam releases appears to be cost prohibitive, but nonetheless is worthy of further investigation. The trade-off between water uses could be minimised, after initial capital expenses, if the freshwater discharge from the power station was transferred via a pipe or canal back to the confluence of the South Esk River and the upper Tamar. A piped solution has ramifications for the efficiency of the power station whereas a canal, flowing adjacent to Home Reach, and which flows in reverse in times of flood, would effectively double the cross-sectional area sustained by the 50 m^3s^{-1} base-flow to 840 m^2 and warrants further investigation.

The occurrence of silt deposition in the upper Tamar estuary, prior to the reduction of the riverine inflow by damming, has been used as an argument against the need to modify power generation to restore environmental flows. However, we contend that earlier upper estuarine silt deposition was the result of the redirection of North Esk River. It has been further argued that increased flows (above historical river flows) through the power station (due to an inter-basin transfer), reduces silt deposition from historical levels, by reducing the upstream movement of silt on asymmetrical tides and redirecting suspended sediment downstream of section 22. We contend that the tidal prism equilibrium model shows that channel cross-sections are independent of other processes or stressors occurring in an estuary, including tidal asymmetry, flocculation, salt wedge, suspended sediment loads or pollutants (O'Brien, 1966). Further, sedimentation would not occur with a regime in equilibrium. This is not to say that a lessening of suspended sediment loads and pollution is not desirable, but their presence merely accelerates the estuary attaining the point of equilibrium.

An increase in the tidal prism could be achieved through the restoration of tidal wetlands associated with the North Esk River. Although a high proportion of the area is now urban and there is little chance of restoring the original tidal prism, an increase in tidal flushing through the creation of a tidally connected lake would improve some values especially if undertaken in conjunction with the delivery of environmental flows. Because we do not know how much the recreational and visual amenity might improve, this activity should be undertaken within an adaptive management framework. Added synergies between ecosystem services would be achieved through the re-instatement of tidal wetlands because these would reduce the flood vulnerability of this region whilst also increasing the biodiversity support function.

A sea level rise of 1 m would not alter the tidal prism (assuming the tidal range remains constant) because much of the upper estuary is confined within flood levees, Cross-sections would move an average 1 m beyond equilibrium depth and deposition up to the same depth would occur. However, low lying areas which are unprotected by dykes would be inundated, and the tidal length of the North Esk River would also increase, having a positive effect on the tidal prism and thereby counteracting deposition.

Sustainable restoration of the upper estuary would be a catalyst for the restoration of the whole estuary. Tidal prism increases in the upper estuary would be magnified downstream and a major mobilisation of silt from the middle to the lower reaches, and beyond, would result.

The Tamar Estuary and Esk Rivers (TEER) Program was established in 2008 to coordinate management and develop solutions and guide investment to protect, maintain and enhance the entire watershed (www.nrmnorth.org.au accessed 9 October 2011). The need to undertake restoration efforts at whole watershed scales to maximise environmental benefits is recommended but often not implemented (Palmer, 2009). Although TEER is an important watershed management initiative, it can be argued that the program's focus on developing a sediment model, to quantify the amount of sediment entering the estuary and to identify the source areas, diverted management attention away from developing an understanding of the fundamental stressors. For this particular environmental problem, devoting greater attention to understanding local processes, also advocated by Palmer (2009), would have been beneficial.

The Need for an Adaptive Restoration Approach

Identification of the processes leading to degradation is the first step in a successful restoration program (Hobbs and Norton, 1996). Getting the science right is essential, but it will not necessarily ensure successful restoration (Brinson, 2006; Palmer, 2009). The need to remove stressors to support the natural recovery of estuarine and coastal habitats has been repeatedly emphasised (Borja et al., 2010; Elliott et al., 2007). However, the irreversible nature of some stressors, (the Trevallyn Dam, re-direction of the North Esk River and urban development on in-filled and drained tidal wetlands) indicate that hysteresis is involved and compensating measures will be required (Elliott et al., 2007). The possibility that restoration measures might result in unexpected consequences or 'ecological surprises' indicates the importance of implementing restoration within a program of adaptive management (Gordon et al., 2008; Zedler, 2006).

Higher freshwater inflows and an increase in the tidal prism are needed to produce eroding rather than depositing conditions. The location and extent of such erosion needs to be carefully monitored to ensure that actions can be modified if erosion starts to occur in non-target areas. Records of sediment contamination, mainly heavy metals from historic mining activities in the upper North Esk (Seen et al., 2004) indicate that identification and treatment of contaminant hotspots may be needed.

Conclusions

Global population growth and increasing economic development means that the demand for all ecosystem services is increasing (Millennium Ecosystem Assessment, 2005). However, management that maximises one ecosystem service often results in a decline in other ecosystem services, creating the need to understand the relationships between multiple ecosystem services in order to maximise synergies and reduce trade-offs (Bennett et al., 2009). The media for delivering provisioning, regulating, and cultural service benefits in the Tamar River estuary and its tributaries is water. The diversion of freshwater away from the upper Tamar estuary to provide hydroelectricity has resulted in the decline of other services valued by the local community. We have suggested some potential strategies to improve declining cultural services and promote the sustainable use of water. However, we recognise that the economic and social importance of the provision of cheap and reliable hydroelectricity means that the management changes needed to restore other ecosystem services need to be very carefully evaluated.

Acknowledgements

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APPENDIX B:

TIDAL HEIGHTS IN HYPER-SYNCHRONOUS ESTUARIES (Kidd et al., 2014)

Abstract

Inconsistencies between datasets are examined with reference to flood tidal elevations in the Tamar River estuary, Tasmania Australia. Errors in a 30 year old commonly cited dataset have been perpetuated in subsequent publications and datasets, and a clarification is herein provided. Elevation of the flood tidal wave as it propagates the estuary is evident in mean tide level and mean sea level, although the analysis is compromised by the temporal differences of the datasets. As sea levels rise due to global warming, the importance of accurate on-going sea level data in any estuary will become more acute.

Keywords

Height Datum, Mean Sea Level, Mean Tide Level, Estuary, Digital Elevation Model, global warming, sea level rise

1. Introduction

Expression of elevation on the surface of the Earth is not a trivial matter, and many countries develop their own systems. In Australia, the system used is the Australian Height Datum (AHD) which is an elevation relative to mean sea level (MSL), as measured at one of 30 reference stations around the Australian coast (Featherstone, 2000). Tasmania has two such stations: Burnie and Hobart **(Figure 1A)**. The geoid to which AHD refers is not a true spheroid but undulates due to variations in the sea surface, caused by ocean currents, the Coriolis force, and meteorological influences. 0m AHD is therefore the MSL at any one of the 30 reference points around Australia, but may vary depending on which station is used as a reference. AHD in Tasmania has been estimated to be 12-26cm offset to that in Victoria (Featherstone, 2000) and suggestions have been made to improve the system (Filmer and Featherstone, 2012). In an estuarine environment, elevations using MSL as the datum can be problematic. Tidal forcing of the flood tide into an estuary may elevate the water body in the manner of a wave breaking on a beach; the kinetic energy of the wave is converted to potential energy as the water runs up the beach, and the maximum elevation attained by the water is higher than mean elevation of the wave. In a hyper-convergent estuary such as the Tamar River **(Figures 1B & 1C)**, the initial kinetic energy is partly dissipated by friction, partly by conversion to potential energy as the tidal amplitude increases (Dyer, 1986), and partly by elevating the waterbody into the upper reaches. This should manifest as an increase in mean tide level (MTL) and MSL (Pugh, 1996). Further, the formation of the M4 and M6 tidal harmonics in the (shallower) upper estuary should produce a difference between MTL and MSL due mainly to M4 (Pugh, 2004). We hypothesized that tidal data for the Tamar River estuary ought to reflect this difference of the amplitude wave to some extent, but it is not apparent in all datasets. We will show that inconsistencies are evident in reports and published papers relating to the Tamar River estuary and also in official Tasmanian Government Digital Elevation Model (DEM) datasets; with some being in error by ~1m whilst some less prominent sources are more accurate. Some of Launceston’s infrastructure is built on old tidal floodplains (Atkins and Vince, 2009; Davis and Kidd, 2012), and an assessment of the risk to these assets depends on an accurate tidal dataset, particularly as sea levels rise as a result of global warming. On a global scale, any inconsistencies between datasets have ramifications for mitigating the effects of climate change, flood control and planning in general.

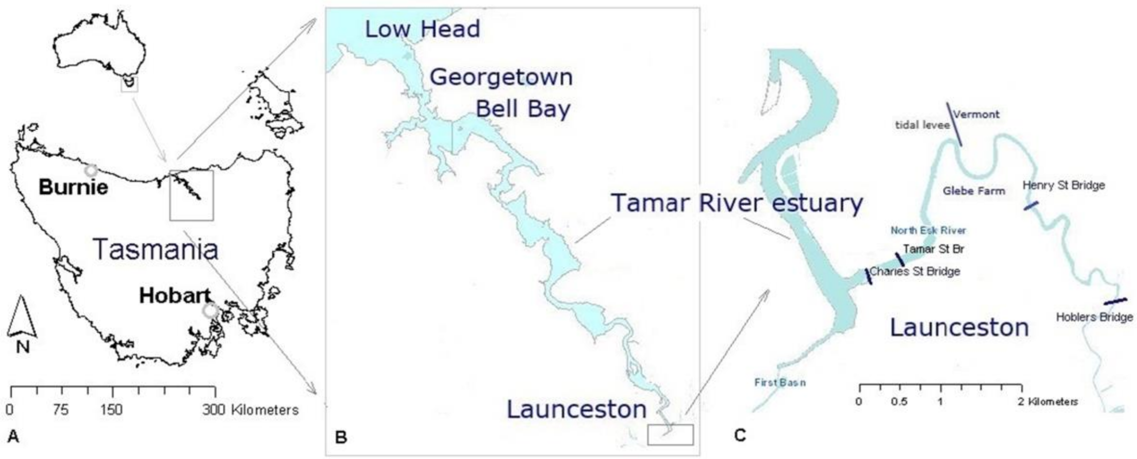

Figure 1 Location of the Tamar and North Esk Rivers estuary system. The North Esk estuary (C) is bounded by a system of flood levees at ~5m AHD and tidal levees at ~2.5m AHD. The Vermont tidal levee withstands spring tides in excess of 2.1m AHD

2. Methods

Various datasets were analyzed for MSL and MTL for each of neap, mean and spring tides. The series analyzed are, Foster et al. 1986 (Foster et al., 1986), BMT-WBM (BMT_WBM, 2008), Bureau of Meteorology (BOM), Australian Hydrographic Service (AHO) (AUS_168, 2012) and a constituent dataset from the Australian Maritime College. The web site www.tide-forecast.com produces tide forecasts for Launceston and Georgetown, using tidal datum of Mean Lower Low Water applicable at each station. We compared one month of data (May 2014) for Launceston and Georgetown. The Australian Bureau of Meteorology (BOM) http://www.bom.gov.au/australia/tides/ produces tide tables for Low Head and predictions "based on limited observations" for Launceston. Where possible, MSL was calculated as the hourly average of tidal heights, and MTL was calculated as the average of maximum and minimum tidal heights over the relevant time span. Figures for neap and spring tides were calculated from the lowest and highest five consecutive days from each month of a dataset.

3. Results

3.1 Foster et al. (1986)

In the 1980s the Launceston City Council in collaboration with other entities, commissioned a report on the sedimentation occurring in the upper reaches (Foster et al., 1986), excerpts of which were peer reviewed and published (Foster and Nittim, 1987). Tidal elevations and gradients from a two month sample from March and April 1985 are shown in **Figure 2**. The Launceston data used by Foster et al. (Foster et al., 1986) had a datum of Low Water Ordinary Spring Tide (LWOST) or -2.26m AHD; 5.238m below an existing bench mark on the City of Launceston's Customs House, which is adjacent to the Charles St Bridge **(Figure 1C)**. The datum at Georgetown is Lowest Astronomical Tide (LAT) which is 1.998m below AHD 0m.

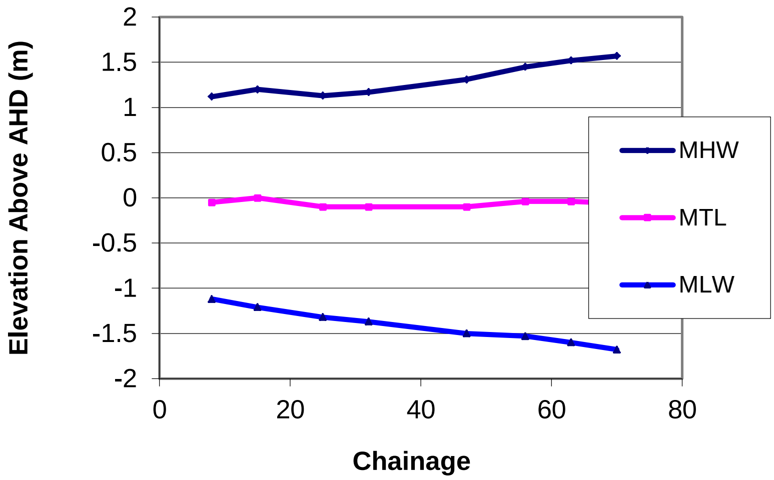

Figure 2. Tidal gradients March/April 1985 (BMT_WBM, 2008)

3.2 BMT-WBM

In 2005 the findings of Foster et al. (Foster et al., 1986) were reviewed by the engineering, architecture and environmental consulting firm GHD, who employed BMT_WBM (2008) to undertake the review and produce a 2D hydrodynamic model of the estuary. They produced a tidal model as an input to the hydrodynamic model which was calibrated against sampled data. Their Figure 4.1 is a duplicate of Foster's with the vertical axis labelled 'Tidal Level (m AHD)', however their model calibration data conflicts with that of Foster et al. (1986) in that it shows a mean spring tide level of 0.48m (AHD). MSL shows an elevation of 0.14m over that of Foster et al. (Foster et al., 1986)

3.3 The Australian Bureau of Meteorology (BOM)

BOM hold hourly data for July and August 1969 for Launceston and a dataset for Low Head from 2003 to 2013 as plotted in **Figure 3**.

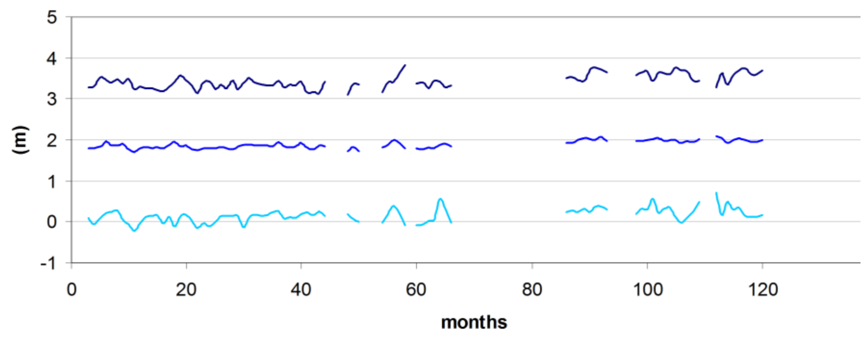

Figure 3 Graph from January 2003 to December 2012 of monthly MSL (middle series), maximum high water (top series) and minimum low water (lower series) at Low Head showing discontinuity and variability of the dataset (BOM)

3.4 Australian Hydrographic Service

The Australian Hydrographic Service produce a navigation chart for the Tamar Estuary (AUS_168, 2012) which includes a table of tidal data for Low Head and Launceston **(Table 1).**

Table 1. Position and tidal data (AUS_168, 2012). With MSL at Low Head at ~2.0m above the datum, then the conversion to AHD requires 2.0m to be deducted from each height. This gives a MHWS for Launceston of 2.1m AHD which is consistent with observation (Figure 5) but a MSL of ~0.6m above the MTL of Foster et al. (Foster et al., 1986)

Station	**Lat. S**	**Long. E**	**Heights**	**in**	**metres**	**above**	**datum**	
			HAT	MHWS	MHWN	MSL	MLWN	MLWS
Low Head	$41^{0}04'$	$148^{0}48'$	3.6	3.3	3.0	2.0	1.0	0.7
Launceston	$41^{0}26'$	$147^{0}08'$	4.6	4.1	3.8	2.6	1.4	1.0

3.5 The Land Information Service of Tasmania (theLIST)

The Tasmanian Government publishes data on www.theLIST.tas.gov.au ; F**igure 4** shows a survey control point layer and a LiDAR Digital Elevation Model (DEM) grid layer. Digital elevation data are available for each of the tiles in the grid and can be checked against the survey control points. The point on the Charles St Bridge **(Figure 1C)** has the added advantage of an adjacent tide gauge using AHD as the datum **(Figure. 5)**. These data are useful to gauge Highest Astronomical Tide (HAT) as the system of tidal levees in the upper estuary withstands all tides, and the elevation of these levees must be at least that of HAT.

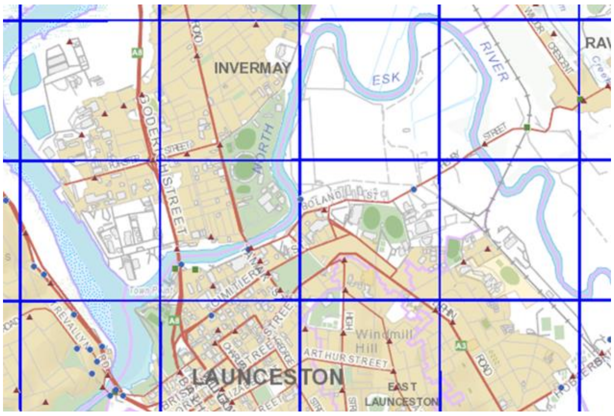

Figure 4. Data layers from www.theLIST.tas.gov.au showing survey control points and DEM grid files; accessed 27/Feb/2014

Figure 5. (left) Photo taken 10.30am (AEDST) 5/Jan/2014 showing tidal gauge calibrated to AHD on the Charles St Bridge and a tidal level of ~2.1m AHD; and tidal gauge on Hobler's Bridge (right) showing a water mark at ~2m AHD

3.6 Australian Maritime College (AMC) tidal constituents

The AMC dataset is a tidal constituent analysis **(Figure 6)** for Low Head, Bell Bay, Tamar St Bridge and Henry St Bridge and is useful for evaluation of Z0 which provides an accurate MSL relative to datum at each station. The combined M4 and M6 components in Launceston are ~0.15m. The data at each station are from differing time spans; Low Head has 46224 records starting 24th March 2003; Georgetown has 354912 records staring 7th July 1965; Tamar St Bridge has 8508 records starting 6th January 2009 and Henry St Bridge has 8872 records starting on the same date.

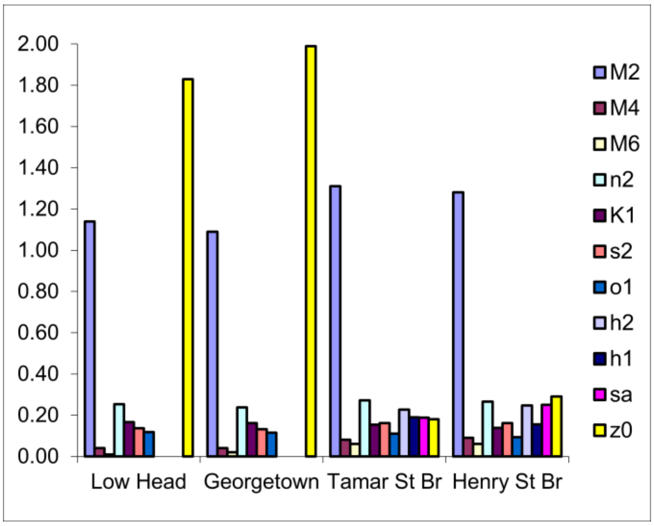

Figure 6. Major tidal constituents by station

3.7 Tide forecasts

The tide forecast data from www.tide-forecast.com and www.bom.gov.au/australia/tides/ are shown in Table 2 and Figures 7 and 8.

Table 2. AHD tidal heights at mouth of the Tamar and Launceston according to various sources and elevations of MTL and/or MSL

		Mouth						Launceston			Elev.	
Data source	LW	HW	MTL	MSL	Datum	LW	HW	MTL	MSL	Datum	MTL	MSL
Foster et al.	-1.12	1.12	-0.05			-1.68	1.57	-0.06			-0.01	
BMT-WBM neap		BOM figure		-0.21	-1.89	-1.16	1.15	-0.01	0.01	-2.26	0.20	
BMT-WBM mean		BOM figure		-0.03	-1.89	-1.45	1.45	0.09	0.08	-2.26	0.12	0.11
BMT-WBM spring		BOM figure		0.24	-1.89	-1.50	1.98	0.48	0.20	-2.26	0.24	
BOM neap	-1.19	0.81	-0.28	-0.21	-1.89	-1.43	1.40	-0.03	0.12	-2.26	0.25	0.33
BOM mean	-1.31	1.16	-0.15	-0.03	-1.89	-1.65	1.62	0.01	0.15	-2.26	0.16	0.18
BOM spring	-1.51	1.62	0.11	0.24	-1.89	-1.82	1.89	0.07	0.12	-2.26	-0.04	-0.12
AUS 168 neap	-1.00	1.00	0.00		-2.00	-0.60	1.80		0.20	-2.00		0.20
AUS 168 spring	-1.30	1.30	0.00		-2.00	-1.00	2.10		0.60	-2.00		0.60
Observation sp.						-1.90	2.10			-2.00		
BOM forecast neap	-1.05	1.04	-0.05		-1.99	-0.89	1.41	0.20		-2.26	0.25	
BOM forecast mean	-1.18	1.20	-0.01	-0.04	-1.99	-1.29	1.57	0.25		-2.26	0.26	
BOM forecast spring	-1.39	1.41	-0.07		-1.99	-1.59	2.06	0.31		-2.26	0.38	
tide-forecast neap	-1.06	0.92	-0.03		-1.99	-1.08	1.34	0.13		-2.26	0.16	
tide-forecast mean	-1.22	1.12	-0.06		-1.99	-1.37	1.66	0.13		-2.26	0.19	
tide-forecast spring	-1.46	1.33	-0.13		-1.99	-1.58	1.80	0.11		-2.26	0.24	
all series neap	-1.12	0.99	-0.13			-1.14	1.45	0.07			0.24	
all series mean	-1.20	1.16	-0.07	-0.03		-1.41	1.66	0.08	0.21		0.14	0.30
all series spring	-1.34	1.38	0.00			-1.68	1.90	0.18			0.16	

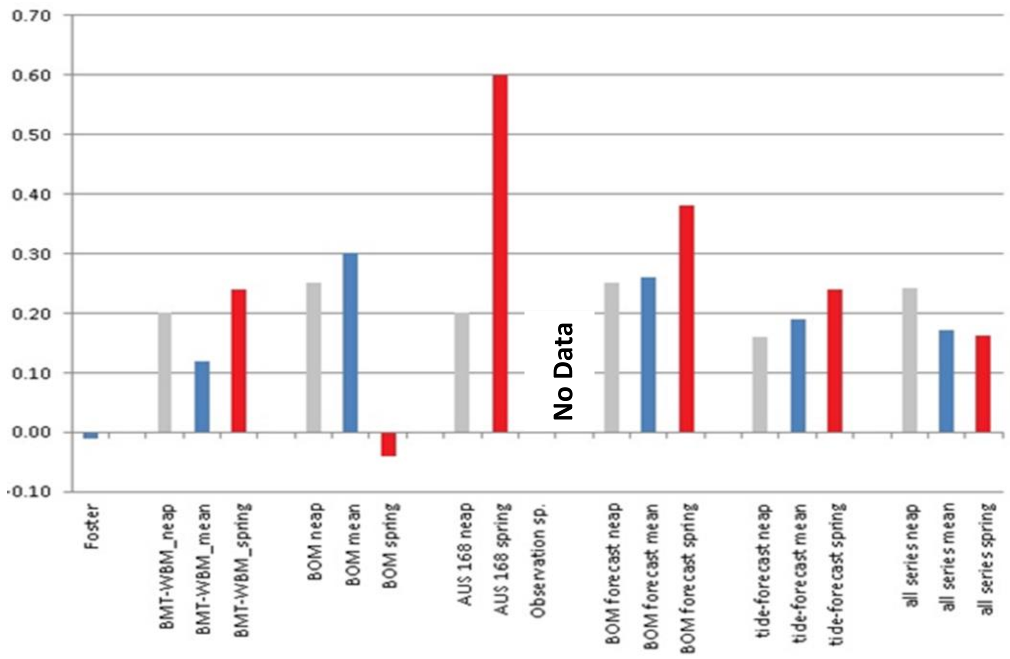

Figure 7. Tidal elevation levels from Low Head (or Georgetown) to Launceston

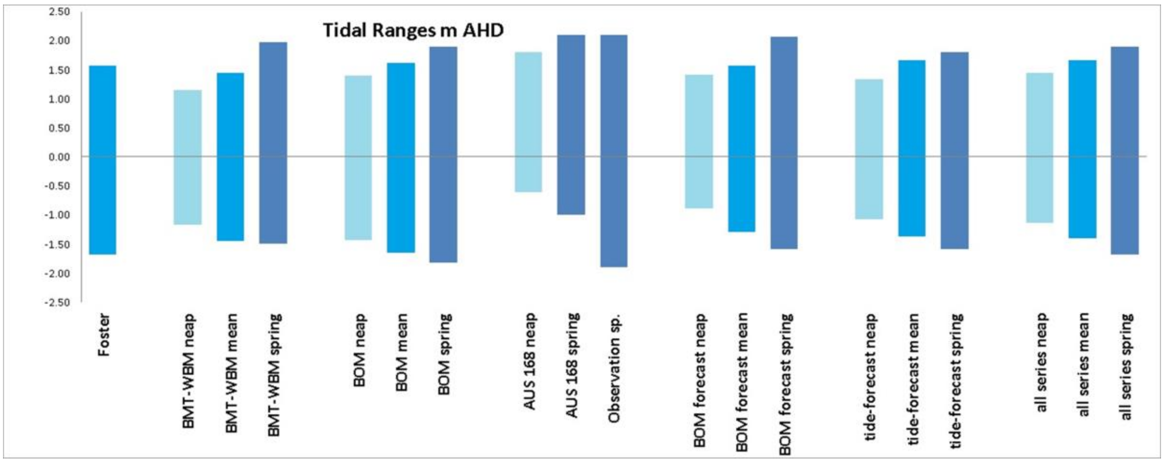

Figure 8. Launceston tidal ranges relative to AHD according to various datasets

3.8 Other data sources

TasWater operate a tidal gauge on the Tamar St Bridge with readings every 3 to 5 minutes. Ellison and Sheehan (2014) produced a single line graph of tidal range in the estuary (their Fig.5) with a vertical axis of m AHD. The figure shows a gradual increase of tidal range from (0,2.5) to (70,3.25). Units are (km, m). The Launceston Flood Authority monitor silt accumulation levels in the upper estuary and produce graphics of the bathymetry. They claim a datum of AHD and show MHWS at 0m AHD.

A further complication in the datasets is the use of Low Head, Georgetown or Bell Bay for the head of the estuary. Each has a unique datum. The constituent dataset shows significant differences between Low Head and Georgetown for Z0, M2 and other major constituents.

4. Discussion

Mean Tidal Level (MTL) is defined as the arithmetic mean of mean high water and mean low water and is distinct from MSL which is defined as the arithmetic mean of hourly heights (Pugh, 2004). AHD is defined by MSL at any of the 30 designated tide stations, and assuming a level sea surface between Burnie and Low Head, then MSL at the mouth ought to be 0m AHD. According to www.dpipwe.tas.gov.au the figure is -0.03m AHD (Table 2). However the 9 year BOM dataset show this to be -0.14m AHD with a datum of -2.0m. This suggests an error in the datum because MSLs at Burnie and Low Head are -0.01 and -0.03m respectively according to **Table 3** and a datum of -1.89m AHD is more likely and is used in the analysis.

Table 3 AHD heights for Tasmanian tide stations (www.dpipwe.tas.gov.au accessed 30 April 2014)

Port	HAT	MSL	LAT
Hobart	**0.86**	**0.05**	**-0.83**
Spring Bay	**0.69**	**-0.02**	**-0.76**
Low Head	**1.62**	**-0.03**	**-2.02**
Stanley	**1.6**	**-0.07**	**-2.06**
Burnie	**1.64**	**-0.01**	**-1.96**

Early cartographers believed that the tidal range was constant from Georgetown to Launceston with a range of 12 ½ ft. (Welsh, 1830), however the Foster et al. report (Foster et al., 1986) included a figure **(Figure 2)** showing how the tidal wave amplitude increases as the wave propagates up the estuary. The figure shows MTL at Low Head of 0m AHD and the (Mean Water Levels (MWL) for high and low tides are scaled inside the vertical axis. However, the data are not supported by other datasets, indicating a problem with the datum or that the sample was too small. The vagaries of the data in **Figure 3** indicate the latter is the case. The tidal wave is composed of hundreds of constituents **(Figure 6)** and it is possible that the constituents will combine such that low tide at Launceston will be lower than the corresponding tide at Low Head, but this is unlikely to be the case for the MTL or MSL. However, the Foster data and the BOM spring data show the opposite; indicating the problematic nature of comparisons using different temporal datasets. **Table 3** gives a summary of sea levels in Launceston and Georgetown by data source and **Figure 7** shows tidal ranges from Low Head to Launceston by data source. Elevations of MTLs from the mouth to Launceston are shown in **Figure 8**.

The LiDAR data from www.theLIST.tas.gov.au are inconsistent. Pixels close to survey control points appear to be accurate, whilst other areas appear to be lower than actual. A tidal levee to the north of Glebe Farm and protecting Vermont tidal flats **(Figure 1C)** withstands all tides and yet the elevation is given as 1.62m AHD, which would just withstand a mean high tide according to the Foster et al. data. However, this is almost 0.5m below the spring tide depicted in **Figure 5**, and allowing for 0.1 to 0.5m clearance of the levee, this height could be in error by as much as 1.0m. Similarly the flood levee between the Charles and Tamar St Bridges **(Figure 1C)** appears to dip from 5.1m (confirmed by the survey marker and the tide gauge) to 4.69m at the point approximately midway between the bridges. However the DEM data confirm the accuracy of the gauge on the Charles St Bridge (fig. 5), and HWS of ~2.1m AHD.

The AHD elevation of the Launceston datum used by Foster et al. (Foster et al., 1986) is -2.26 m AHD, which is also the datum used by BOM (P. Davill 2014, personal communication). The DEM level of the tidal levee at Vermont tidal flat, is roughly consistent with mean high water of Foster et al. (Foster et al., 1986) and BMT-WBM, indicating that the Foster data may have been used for calibration in that area. For data where only HWS was observable, LWS was calculated from an assumed range of 4.0m as per BOM and BMT-WBM datasets. MHWS from AUS 168 is consistent with all observational datasets; whilst MLWS appears too high. The other sources of data, including TasWater dataset, the LFA data and the Ellison and Sheehan graph did not provide information that was useful to this analysis, leaving the remaining datasets, each with their own accuracy at a particular level.

MSL was not available from all datasets as this calculation requires hourly readings. Of all datasets, Foster et al. (Foster et al., 1986) is the only one which does not show an elevation of the mean tide from Low Head to Launceston. This is unfortunate as it is the dataset most often cited. All other datasets show an elevation of MTL and MSL from the mouth to

Launceston, which confirms our hypothesis that tides in the estuary undergo an elevation as well as amplification whilst propagating up the estuary. The BOM dataset confirms Pugh's (Pugh, 2004) assertion that the MTL and MSL difference ~equates to the amplitudes of the M4 and M6 tidal harmonics in the upper estuary (~0.15m).

Conclusion

Our results confirm that the figure for tidal heights produced by Foster et al.(1986) is inconsistent with data from other sources. In particular, the mean water level is inconsistent with data from official navigation charts (AUS_168, 2012), predictions from www.tide-forecast.com and BOM, elements of the DEM published on www.theLIST.tas.gov.au , historical data from BOM and our own observations. The Foster et al.(1986) figure correctly depicts relative water levels or MWLs and tidal ranges, and diagrams of this form are used in the literature (Dyer, 1997; Toffolon, 2002). Other sources confirm our assertion that the water-body (manifest as MTL and MSL), is elevated as it is forced into the ever narrowing estuary. Historical data from BOM puts the elevation of MSL at 0.18m; allowing for an error in the datum confirmed by the constituent analysis. Spring tides do not necessarily produce a greater elevation than neap tides. This is due to a large variation in MTL at the mouth between neap and spring tides. Confusion between AHD, MTL, MWL and MSL (not to mention neap, mean and spring tides) is unfortunate and may explain errors in the calibration of a publicly available DEM. Parts of the model are consistent with survey control points while other points distant from the controls are low, with functioning tidal levees below known HWS level. In the absence of an official BOM tidal station in Launceston, caution should be observed when using any elevation or tidal dataset, as MSL cannot be assumed as ~0m AHD. The dynamics and complexities of the estuarine environment, present challenges to accurate measurement of tidal height. The installation and maintenance of an official tide gauge in the upper estuary is essential for monitoring of on-going sea level rise, the rate of which can only increase as a result of global warming; and so that planning and mitigation can be implemented in a cost effective manner.

Acknowledgements

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APPENDIX C:

200 YEARS OF MUD AND MISUNDERSTANDING (Kidd and Davis, 2015)

Appendix C has been removed for copyright or proprietary reasons.

It was published as: Kidd, I. M., Davis, J., 2015. 200 years of mud and misunderstanding, Tasmania 40°south, 14-21

APPENDIX D:

IDENTIFICATION OF PROBLEM, SYMPTOMS, CAUSES AND ROOT-CAUSES

Root-cause analysis applied to the upper Tamar

Symptoms of a problem are identifiable because they return once removed, whereas remove root-cause(s) and the problem is solved (Paradies et al., 2012). Paradies et al. (2012) define a root-cause as:-

"*..the most basic cause that can be reasonably identified that management has control to fix and when fixed, will prevent or significantly reduce the likelihood of the problem's recurrence*."

The upper Tamar has been dredged and raked since the 1880s but the silt always returns, indicating that silt is a symptom resulting from an underlying root-cause or multiple root-causes. Practical methods have been developed for identification of root-causes. One technique is "5-Whys" (asking "why?" five times in a series to get to the root-cause of the problem) (Fantin, 2014; Ohno, 1988) (Fig. D1); another developed in the Japanese car industry is the Ishikawa diagram (Ishikawa, 1990) also known as the fishbone, herringbone or cause-and-effect diagram. An application of the 5-Whys method to the Tamar problem is at Table D1. The identification of a problem will depend on the observer, with some observers (e.g. a visitor) not seeing a problem at all. In the case of the Tamar, a photographer may see interesting patterns in the silt; a keel boat owner might see insufficient depth for navigation or a small water-body whereas a local resident might see a build-up of silt. Each view point is used as a starting point, several answers may exist for each 'why' and more than one root-cause may be found. As previously stated, the loss of amenity in the upper Tamar has multiple causes (silt, pollution, sewage, turbidity, weed infestation) but this analysis is confined to the siltation issue. Complex ecological or environmental problems require more comprehensive analysis (Norris et al., 2008) or adaptive management (Walters, 1986) and the 5-Whys technique is not often used for environmental problems. In this instance the processes are physical, rather than chemical or biological and the methodology found the same root-causes as Davis and Kidd (2012); a reduction in freshwater flows and loss of tidal prism due to canalisation of the upper estuary.

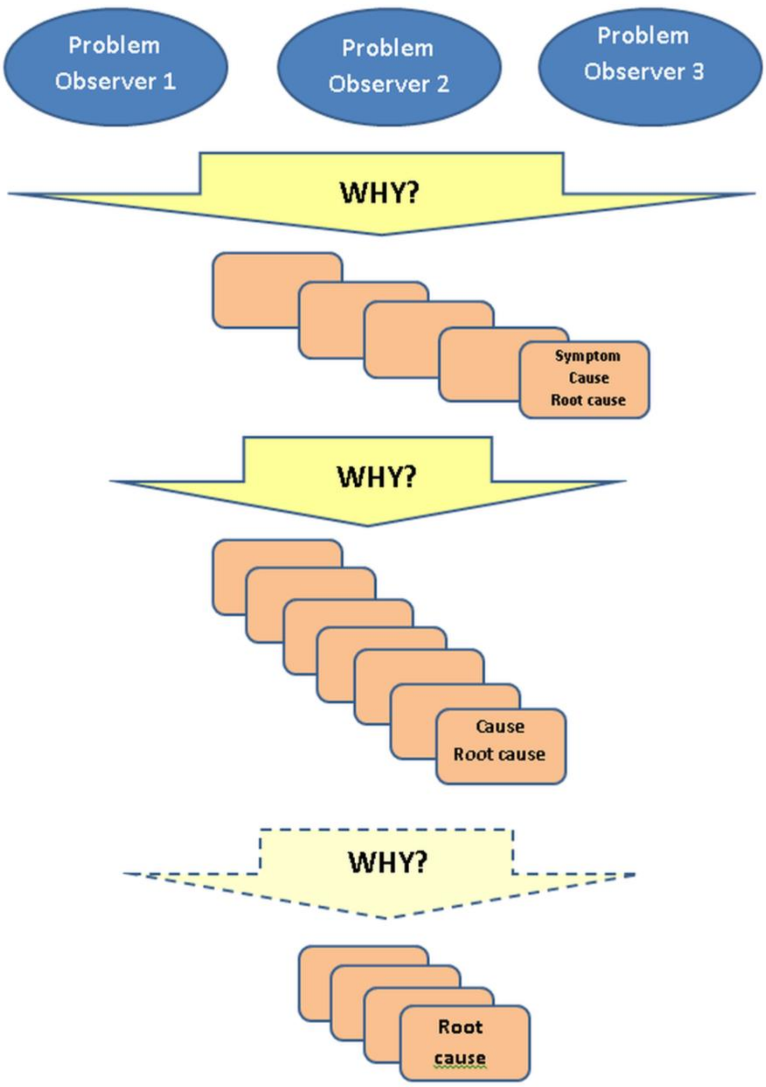

Fig. D1 Generic application of the 5-whys process, showing multiple observations (problems), symptoms, causes and root-causes. Root-causes are normally found within 5 iterations

Table D1 5-Whys applied to the loss of amenity problem in the upper Tamar River estuary

Root Cause Analysis Using 5 WHYs Method- applied to the Yacht Basin

Observer	THE SITUATION	1		2		3		4		5		cause	result
Keel boat owner		**why**	poor scouring	**why**	flood effects reduced	**why**	50 cumecs thru Pwr St	**why**	dam			**dam**	**root-cause**
					low water velocity	**why**	low fresh flow	**why**	dam			**dam**	**root-cause**
water too shallow			low flushing to Bass Strait	**why**	low water velocity	**why**	low fresh flow	**why**	dam			**dam**	**root-cause**
			low tidal effects	**why**	small tidal prism	**why**	end of estuary					**end of estuary**	
							in-fill					**in-fill**	**hysteresis**
							N Esk diversion					**N Esk diversion**	**hysteresis**
Tourist boat skipper			low fresh water flow	**why**	dam							**dam**	**root-cause**
Problems with channel markers			Small Cross sectional area	**why**	low flow	**why**	low fresh water flow	**why**	dam			**dam**	**root-cause**
						why	low salt water prism	**why**	end of estuary			**end of estuary**	
Fish			excessive deposition	**why**	low flow velocity	**why**	low salt water prism	**why**	end of estuary			**end of estuary**	
									N Esk diversion			**N Esk diversion**	**hysteresis**
not much water							low fresh water flow	**why**	dam			**dam**	**root-cause**
					high sediment loads	**why**	sewage inputs	**why**	flow unable to cope	**why**	low flow	**dam**	**root-cause**
Rower	**Small Channel**						land use changes	**why**	insufficient flow	**why**	dam	**dam**	**root-cause**
loss of rowing course							tidal asymmentry	**why**	sediment not flushed	**why**	low flow	**dam**	**root-cause**
					flocculation	**why**	tidal asymmentry	**why**	sediment not flushed	**why**	low flow	**dam**	**root-cause**
Fisherman							worse in low flows	**why**	low flow	**why**	dam	**dam**	**root-cause**
boat stuck in mud					catchment issues	**why**	land use changes	**why**	Insufficient flow	**why**	dam	**dam**	**root-cause**
					excessive dredging	**why**	equilibrium imbalance	**why**	sustainable flow issue	**why**	dam	**dam**	**root-cause**
			equilibrium imbalance	**why**	channel tending smaller	**why**	low salt water prism	**why**	end of estuary			**end of estuary**	
					flow not at sustainable level	**why**	low fresh water flows	**why**	dam			**dam**	**root-cause**
			low salt water	**why**	low tidal prism	**why**	end of estuary					**end of estuary**	
							in-fill					**in-fill**	**hyteresis**
							N Esk diversion					**N Esk diversion**	**hysteresis**
					no salt wedge effect	**why**	end of estuary					**end of estuary**	
Local resident		**why**	poor scouring	**why**	flood effects reduced	**why**	50 cumecs thru Pwr St	**why**	dam			**dam**	**root-cause**
					low water velocity	**why**	low fresh flow	**why**	dam			**dam**	**root-cause**
							N Esk Diversion					**N Esk diversion**	**hysteresis**
silt increasing			low flushing to Bass Strait	**why**	low water velocity	**why**	low fresh flow	**why**	dam			**dam**	**root-cause**
	too much silt		low tidal effects	**why**	small tidal prism	**why**	end of estuary					**end of estuary**	
							in-fill					**in-fill**	**hysteresis**
							N esk diversion					**N Esk diversion**	**hysteresis**
tourist			low fresh water flow	**why**	dam							**dam**	**root-cause**
interesting patterns			Small Cross sectional area	**why**	low flow	**why**	low fresh water flow	**why**	dam			**dam**	**root-cause**
						why	low salt water prism	**why**	end of estuary			**end of estuary**	
Bird			excessive deposition	**why**	low flow velocity	**why**	low salt water prism	**why**	end of estuary			**end of estuary**	
							N Esk diversion					**N Esk diversion**	**hysteresis**
feeding opportunities							low fresh water flow	**why**	dam			**dam**	**root-cause**
					hysteretic cause		natural feature		root-cause				

APPENDIX E:

LAKE BATMAN PROJECT

Stopping the tidal flow with a barrage is a clear example of working against nature and the negative impacts can be severe. The morphological impact of the Lake Batman proposal for example, is demonstrated by a simple application of FORM (Fig. 18). The tidal prism at the new confluence of North Esk and Tamar Rivers is approximately 1,000,000 m^3 compared with over 4,000,000 m^3 presently.

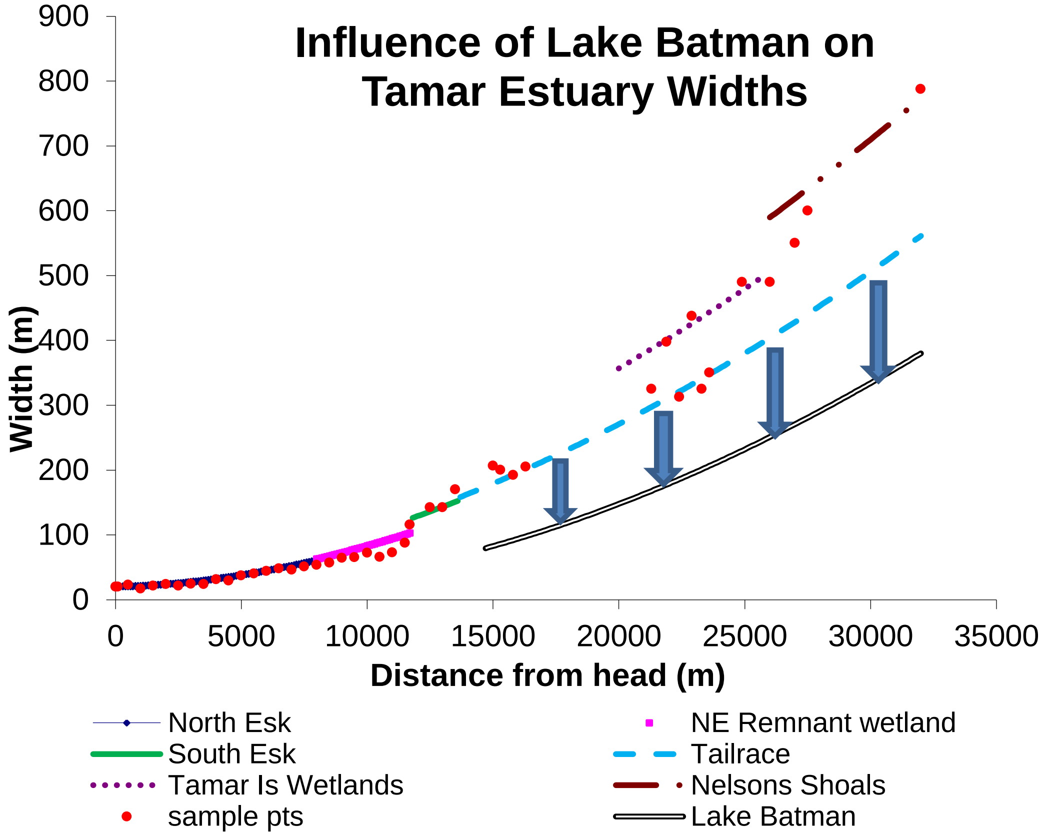

Fig. E1 FORM applied to the Lake Batman proposal showing contraction of the channel width beyond the barrage at Stephenson's Bend. The influences of downstream water storages are not shown for clarity

This project provides an increase in physical amenity for Home Reach, the Yacht Basin and the lower North Esk River but downstream of Stephenson's Bend the morphological trade-off is severe.

APPENDIX F:

POTENTIAL TIDAL AND FLOOD INUNDATION IMPACTS ON LAUNCESTON AND SUBURBS

Potential Tidal & Flood Inundation Impacts on Launceston and Suburbs

Ian Kidd and Prue Hamill JFA240/545 2014

Introduction

The site. Parts of Launceston suburbs (Fig. 1) such as Invermay, Inveresk and Newstead have elevations below Mean High Water Springs (MHWS) (Ellison and Sheehan 2014) or 2.1 m AHD (Fig. 2). These areas are protected from inundation by an extensive system of tidal levees (Fig. 3), some of which have been in place since the early 1800s (Davis and Kidd 2012). Since 1806 some low lying areas have been in-filled by dredge spoil, refuse disposal and clean fill. The urban area is further protected by extensive flood levees which have an elevation of ~5m AHD.

Tidal Heights….The mean tidal range varies from 2.34 m at Low Head to 3.25 m in Launceston (Foster et al. 1986). Functioning tidal levees must be somewhat higher than MWHS. This level is now >14 cm over the elevation in 1806 (Pugh et al. 2002) and somewhat less than future levels, as this trend continues and is exacerbated by global warming. Despite significant efforts being undertaken by many local governments in coastal Australia (Gurran et al. 2011) development on areas at risk continues with mitigation as the main strategy. This project examines the potential inundation from tides of the low lying areas of Launceston should a tidal levee fail; and the potential inundation from floods should a flood levee fail (Atkins and Vince 2009). The evaluation considers the quality and accuracy of the data available and we hypothesise that inaccuracies in the data set will be exacerbated in the analysis of land use impacts. Analyses concerning urban data such as road infrastructure should not be unduly affected by data errors as these areas tend to be in close proximity to survey control markers.

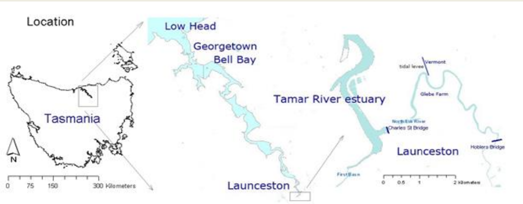

Figure 1 Location of the Tamar and North Esk Rivers estuary system. The North Esk estuary is bounded by a system of flood levees at ~5m AHD and tidal levees at ~2.5m AHD. The Vermont tidal levee withstands spring tides in excess of 2.1m AHD.

Methods

1. Digital elevation data from TheLIST (60 files) was uploaded into ArcGIS to create a Digital Elevation Model (DEM) of the Tamar Estuary (Fig 4).
2. A Mosaic was created from the individual files which was used to create 6 elevation layers, 1.5 m, 1.96 m, 2.1 m, 2.24 m, 2.5 m and 3.0 m using 'Raster Calculator'.
3. Each raster elevation layer was converted to a vector polygon using 'Raster to Polygon' (6 layers).
4. The Mosaic was converted to a Hillshade ,using 'Hillshade' in Spatial Analyst, and used as the background for each elevation polygon.
5. A land use layer, 'Zoning', was added and clipped to each elevation polygon using the 'Intersect' tool in Analysis Tools.
6. Land use category 'Roads' had 'noData' in the 'Zoning' layer. A 'Symmetrical Difference' was performed; 'Zoning' was updated against a polygon outline of the mosaic to give a polygon representing roads only. The area of this polygon was calculated in the attribute table. This layer was then clipped to each elevation polygon using the 'Clip' tool in Geoprocessing.
7. Data from each elevation polygon was downloaded to Excel™ and graphs were produced for analysis.
8. A Survey Control Pt. layer and a Low Pt. layer were compared using the Kriging function to estimate errors apparent in the DEM data.

Data Sources

1. DEM Data & Survey Control Points: theLIST at http://maps.thelist.tas.gov.au/listmap/app/list/map 'Climate Futures LIDAR Coverage'
2. 100 Year Flood: T drive at AMC '1in100_Year_Flood.shp
3. Land Use: T drive at AMC 'Zoning.shp'
4. Projected Tidal Elevations: (Pugh et al. 2002)
5. Roads: Created data source using 'Zoning.shp' (Refer to Methods)

Results

As expected the land area lost to inundation increased with the increasing tide (Fig. 5 & 6). A 3m tide is comparable to the '1 in 100 year flood' (Fig. 6) with the land lost to each almost identical. A Kriging analysis of the DEM errors (Fig 7) indicated minimal errors close to major infrastructure.

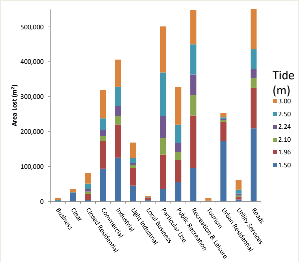

Figure 5 Graphs showing the land area lost to inundation for each tidal elevation.

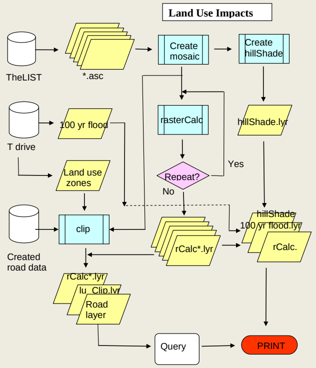

Figure 4 Flow diagram of analytical process.

Figure 2 A 2.1m tide flooding Tamar Marine slipway.

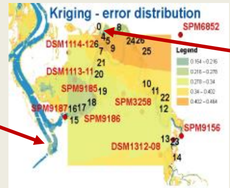

Figure 7 A DEM error distribution showing minimum errors near survey control markers.

Figure 3 Vermont levee withstanding a 2.1m tide.

Discussion

The Launceston planning scheme seeks to: "identify known or foreseeable impacts of climate change such as sea level rise, and increased flood risk and adopt a precautionary approach to the location of new development" (www.launceston.tas.gov.au). This objective is not met with new development occurring in areas of high risk. Most at risk are industrial, commercial and business sectors, whilst urban residential is largely safe from all but the highest tides.

Conclusion

This analysis confirms that increasing elements of Launceston's infrastructure are at risk from rising sea levels. Local Government have chosen a mitigation rather than a planning approach in dealing with the issue, by relying on tidal and flood levees to protect vital infrastructure and property. We found the accuracy of the data used (DEM) sufficient for the purpose as the evident errors tended to be distant from aforesaid infrastructure.

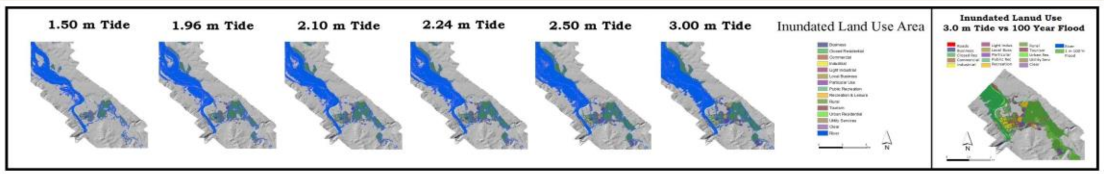

Figure 6 Maps showing the potential land-use impacts from tidal inundation at various amplitudes. The last map compares the loss of land due to a 3.0 m tide with that from a '1 in 100 year flood'. The category 'Rural' has been excluded due to its large size which did not allow proper display of the other land use categories.

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